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JOINING OF NICKEL-BASE ALLOYS

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JOINING OF NICKEL-BASE ALLOYS

by

R. M. Evans

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

FOREWORD

The information in this report was obtained from reports filed at the Defense Metals Information Center at Battelle Memorial Institute, Columbus, Ohio, and from the published literature. A cutoff date of October 1, 1962, was used and information received after this date is not covered. All of the data on the individual alloys that are discussed may not be equally reliable; some alloys have been the subject of greater study than others. In many cases tabulations, graphs, and illustrations have been reproduced in their original form because no need for alteration was found. The author wishes to express his appreciation to those who originally placed this information in the literature. Comments on the material contained, contributions of more recent material, and suggestions for future reports are solicited.

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JOINING OF NICKEL-BASE ALLOYS

SUMMARY

The key to the success of many devices that are to be used in corrosive or high-temperature environments is often an ability to properly weld the nickel-base alloys. Alloys such as Monel, Inconel, etc., that do not depend upon relatively complex metallurgical reactions to obtain their desirable properties are not difficult to weld if proper procedures are used. Alloys which are relatively new (René 41, Hastelloy R-235, Inconel X, etc.) and do depend on complex metallurgical reactions to develop their useful properties present many joining problems. This report covers, in a general way, the criteria for the successful fabrication of several alloys which fall in each category. Fusion welding, resistance welding, and brazing are covered. The welding of dissimilar nickel-base-alloy combinations and repair welding are also discussed.

INTRODUCTION

This report summarizes available information on the processes and procedures used for joining nickel-base alloys. Joining of these alloys, particularly those having good high-temperature properties, is important to practically all missile- and rocket-fabricating procedures. The major emphasis in the report is placed on these high-temperature alloys, but for completeness, most of the important nickel-base alloys which may be joined are included. Thus both superalloys and alloys used mainly for corrosion-resistance are discussed. For example Monel and the Illiums are only rarely used for elevated-temperature service while René 41 is used almost exclusively for this type of service. The alloys are divided into groups which correspond to the basic metallurgical factors involved when welding them. These factors are the same as those which control their major mechanical properties and, consequently, require no newly devised separations.

Table 1 is a tabulation of the nickel-base alloys grouped according to the mechanism used to obtain the maximum possible elevated-temperature strength. Alloys such as Monel, Inconel, etc. , are not normally strengthened by heat treatment. They acquire strength mainly from cold work and relatively minor compositional changes. The application of heat either during joining or use will have a deleterious effect on the desirable mechanical properties. Other solid-solution-hardening alloys such as the Hastelloys are single-phase alloys which are strengthened usually by the addition of elements which inhibit plastic deformation; some age hardening may be encountered also. The heat from joining operations will lower the mechanical properties of these alloys unless they are already in the annealed condition. They pose no great problems when welding, etc. Precipitation-hardening nickel-base alloys obtain their strength through the formation of a dispersed second phase within the solid-solution matrix.

A discussion of the intricacies of the strengthening mechanisms in nickel-base high-temperature alloys is found in DMIC Report 153.[(1)*] Here, it is only necessary to emphasize the importance of heat treatments to the success of many of these alloys. Because of the complex composition, a wide variance in properties can be obtained by altering the thermal treatment given any one alloy. Consequently, the thermal experiences produced by joining operations must be carefully adjusted to and sequenced for the particular alloy being joined, and to its intended use.

EFFECT OF ALLOYING ELEMENTS ON WELDABILITY

It is beyond the scope of this report to cover all of the effects of alloying elements in nickel and nickel-base alloys. But it is useful to consider the effect of major alloying elements on their weldability. A knowledge of the effects of about 18 elements is necessary to an understanding of the welding characteristics of nickel-base alloys. Pease[(2)] and Shelton[(3)] have summarized these effects on fusion welding as shown in Table 2 and discussed in the following paragraphs.

* References are listed on page 67.

TABLE 1. CHEMICAL COMPOSITION OF NICKEL-BASE ALLOYS

Trademark or Trade Name	Composition, weight per cent											
	Ni[a]	C	Cr	Mo	Fe	Co	W	Al	Ti	Cb[b]	Mn	Si	Others
					Alloys Hardened Principally By Solid Solution								
Monel	63-70	0.30	--	--	2.50	--	--	--	--	--	2.00	0.50	Bal Cu
	67	0.15	--	--	1.4	--	--	--	--	--	1.0		30 Cu
Inconel	72[d]	0.15	14-17	--	6.0-10.0	--	--	--	--	--	1.0	0.5	0.5 Cu
	76	0.04	15.5	--	7.0	--	--	--	--	--	0.35	0.2	
Nimonic 75	71-78	0.08-0.15	18-21	--	5.0	--	--	--	0.2-0.6	--	1.0	1.0	0.5 Cu
	76	0.12	20	--	2.4	--	--	0.06	0.4	--	0.4	0.6	
Illium R	68	0.05	21.0	5.0	1.0	--	--	--	--	--	1.25	0.70	3.0 Cu
Illium G	56	0.20	22.5	6.4	6.5	--	--	--	--	--	1.25	0.65	6.5 Cu
Hastelloy Alloy B	Bal	0.05-0.12	1.0	26-30	4.0-7.0	2.5	--	--	--	--	1.0	1.0[c]	0.2-0.6 V
	61	0.10	1.0	28	5.0	--	--	--	--	--	0.8	0.7	
Hastelloy Alloy C	Bal	0.08-0.15	14.5-17.5	15-18	4.0-7.0	2.5	3.0-5.25	--	--	--	1.0	1.0[c]	0.35 V
	57	0.10	16	17	5	--	4	--	--	--	0.8	0.7	
Hastelloy Alloy D	Bal	0.12	1.0	--	2.0	1.50	--	--	--	--	0.5-1.25	8.5-10.0	2.0-4.0 Cu
	82	0.10	--	--	1.0	1.50	--	--	--	--	1.0	9.0	3.0 Cu
Hastelloy Alloy F	44	0.05-0.12	21-23	5.5-7.5	Bal	2.5	1.0	--	--	1.75-2.50	1.0-2.0	1.0[c]	--
Hastelloy Alloy X	Bal	0.05-0.15	20.5-23	8.0-10.0	17-20	0.5-2.5	0.2-1.0	--	--	--	1.0	1.0[c]	--
	45	0.10	22.0	9.0	20	1.5	0.6	--	--	--			--
Hastelloy Alloy N	67-72	0.04-0.08	6.0-8.0	15-18	5.0	--	--	--	--	--	0.8	0.5[c]	Al + Ti=0.5
					Alloys Capable of Precipitation Hardening								
K Monel	63-70	0.25	--	--	2.00	--	--	2.0-4.0	0.25-1.00	--	1.50	1.00	Bal Cu
	66	0.15	--	--	0.9	--	--	2.75		--	0.85	1.0	29 Cu
Inconel X	70[c]	0.08	14-17	--	5.0-9.0	1.0	--	0.4-1.0	2.25-2.75	0.7-1.2	1.0	0.5	0.5 Cu
	73	0.04	15	--	7		--	0.9	2.5	0.9	0.7	0.3	

TABLE 1. (Continued)

Trademark or Trade Name	Ni[(a)]	C	Cr	Mo	Fe	Co	W	Al	Ti	Cb[(b)]	Mn	Si	Others
						Composition, weight per cent							
						Alloys Capable of Precipitation Hardening (Continued)							
Inconel 702	75-81 78	0.1 0.1	14-17 15.5	-- --	2.0 2	-- --	-- --	2.75-3.75 3.25	0.25-1.0 0.65	-- --	1.0 0.1	0.7 0.25	0.5 Cu
Alloy 713C	66-77 72	0.20 0.12	11-14 13	3.5-5.5 4.5	5.0 1	-- --	-- --	5.5-6.5 6	0.25-1.25 0.6	1.0-3.0 2.25	1.0 0.15	1.0 0.4	0.02 B, Zr
DCM Alloy	63-70 68	0.08 0.05	14-16 14.3	4.5-6.0 5.3	4.0-6.0 4.6	-- --	-- --	4.4-4.8 4.4	3.35-3.65 3.4	-- --	0.10	0.15	0.07-.09 B 0.08 B
Hastelloy Alloy R-235	Bal 63	0.16 0.15	14-17 15.5	4.5-6.5 5.5	9.0-11.0 10.0	2.5	-- --	1.75-2.25 2	2.25-2.75 2.5	-- --	0.25[(c)]	0.6[(c)]	0.005 B[(c)] --
Incoloy 901	40-45 42	0.10	11-14 13.0	5.0-7.0 6.0	Bal 28	-- --	-- --	-- --	2.0-3.0 2.4	-- --	-- --	-- --	
D 979	45	0.05	15.0	4.0	27.0	--	4.0	3.0	1.0	--	0.30	0.30	0.01 B
Waspaloy	56	0.05	19.0	4.3	1.0	14.0	--	1.3	3.0	--	0.70	0.40	0.005 B 0.06 Zr
Nimonic 80	70-77 76	0.1 0.05	18-21 20	-- --	5.0 0.5	2.0	-- --	0.5-1.8 1.0	1.8-2.7 2.3	-- --	1.0 0.7	1.0 0.5	-- --
Nimonic 80A	70-77 75	0.1 0.04	18-21 21	-- --	5.0 0.5	2.0	-- --	0.5-1.8 0.6	1.8-2.7 2.5	-- --	1.0 0.7	1.0 0.5	-- --
Nimonic 90	50-62 58	0.1 0.10	18-21 19.5	-- --	5.0	15-21 18.0	-- --	0.8-2.0 1.2	1.8-3.0 2.4	-- --	1.0	1.5[(c)]	-- --
Nimonic 95	50-62 50	0.15	18-21 20.0	-- --	5.0	15-21 20.0	-- --	1.4-2.5 2.0	2.3-3.5 3.0	-- --	1.0	1.0[(c)]	0.5 Cu
Nimonic 100	50-62	0.30	10-12 11.0	4.5-5.5 5.0	2.0	18-22 20.0	-- --	4.0-6.0 5.0	1.0-2.0 1.5	-- --	-- --	0.5[(c)]	-- --

TABLE 1. (Continued)

Trademark or Trade Name	Ni[a]	C	Cr	Mo	Fe	Co	W	Al	Ti	Cb[b]	Mn	Si	Others
						Alloys Capable of Precipitation Hardening (Continued)							
Inconel 700	40-50	0.16	13-17	1.0-4.5	4.0	24-34	--	2.5-3.5	1.75-2.75	--	2.0	1.0[c]	--
	45	0.16	15.0	3.0	1.5	29.0	--	3.0	2.2	--	0.1	0.25	--
Udimet 500	46-55	0.15	15-20	3.0-5.0	4.0	13-20	--	2.5-3.25	2.5-3.25	--	0.75	0.75[c]	0.005 B 0.06 Zr
	52	0.12	19.0	4.0	2.0	19.0	--	3.0	3.0	--	0.7		0.005 B 0.05 Zr
Udimet 700	46-55	0.15	13-17	4.5-5.75	1.0	17-20	--	3.75-4.75	3.0-4.0	--			0.10 B[c]
	53	0.12	15.0	5.1	0.75	18.5	--	4.25	3.5	--			0.08 B
Unitemp 1753	51	0.25	16.5	1.5	9.5	7.5	8.5	2.0	3.1	--			0.008 B 0.05 Zr
	Bal	0.02-0.28	15.5-17.5	1.0-2.0	7-11	6.5-8.5	7.5-9.5	1.75-2.25	2.9-3.4				0.002-0.010 B 0.02-0.10 Zr
M252	51-57	0.10-0.20	18-20	9.0-11.0	5.0	9.0-11.0	--	0.5-1.25	2.25-2.75	--	0.5-1.5	0.3-1.0	
	55	0.15	19.0	10.0	2.0	10.0	--	1.0	2.5	--	1.0	0.7	0.005 B 0.06 Zr
René 41	52-58	0.06-0.12	18-20	9-10.5	5.0	10-12	--	1.5-1.8	3.0-3.3	--	0.5	0.5[c]	0.01 B
	55	0.10	19.0	10.0	1.0	10.0	--	1.5	3.0	--	0.05	0.1	0.005 B
Nicrotung	61	0.10	12.0	--		10.0	8.0	4.0	4.0	--			0.05 B 0.05 Zr
Inconel W	75	0.03	15.0	--	7.0	--	--	0.06	2.35	--	0.55	0.2	--
Inconel 718	50-55	0.01[e]	17-21	2.8-3.3	Bal	--	--	0.2-1.0	0.3-1.3	4.5-5.75	0.50[e]	0.75[e]	0.75 Cu[e]
	54	0.05[e]	--	--	--	--	--	--	--	--	--	--	0.03 S[e]

Note: When two compositions are given, those in top line are maximum compositions or ranges; those in bottom line are typical compositions.

(a) Includes small amount of cobalt unless otherwise specified.

(b) Includes tantalum.

(c) Indicates minimum amount.

(d) Indicates maximum amount.

TABLE 2. EFFECT OF ELEMENTS USUALLY PRESENT IN NICKEL AND HIGH-NICKEL ALLOYS ON THEIR WELDABILITY[2,3]

Beneficial	No Real Effect[a]	Variable	Harmful
Cb	Mn	Al	S
Mg	Cu	Ti	P
	Cr	C	Pb
	Fe	Mo	Zr
	Co	Si	B

(a) Within normal concentration ranges.

Magnesium - Magnesium sulfides having melting points much higher than the nickel sulfides are formed during welding. Thus, sulfur fixation is accomplished with magnesium. Unfortunately, the recovery of magnesium is poor, especially when using covered electrodes.

Columbium - Columbium is used to prevent the occurrence of hot cracking in nickel-iron-chromium alloys containing silicon. The amount of columbium required varies with the nickel/iron ratio. The higher the ratio the more columbium required.

Lead - Lead causes hot shortness in nickel-alloy weld metal. It is seldom found in high-quality base or filler metals.

Sulfur - Sulfur also causes hot shortness. It is probably the most offensive element encountered when welding nickel-base alloys. Sulfur has a very limited solubility in nickel and also forms low-melting sulfide materials which embrittle the alloy by collecting at grain boundaries. Vacuum melting of the alloys or magnesium fixation are means of overcoming the ill effects of sulfur. High-quality nickel-base materials may be ruined by poor removal of sulfur containing machining compounds, crayon marks, or shop dirt before welding.

Phosphorus - Phosphorus, like lead, is seldom found in nickel-base alloys. Phosphorus in very low concentrations can cause weld hot cracking. Generally, its detrimental effects are similar to those of lead and sulfur.

Boron - Boron cannot be considered completely detrimental to nickel-base alloys because it has been added to improve the high-temperature mechanical properties. The presence of boron in even very low concentrations causes cracking of both the weld metal and the heat-affected zone.

Zirconium - Zirconium, like boron, can be added to improve the high-temperature mechanical properties. Such additions ruin weldability. A few tenths of 1 per cent zirconium makes nickel-base alloys very weld-crack sensitive. Zirconium-nickel alloys are not fusion weldable.

Carbon - Carbon in the nonchromium-bearing nickel alloys may cause trouble if the service temperature is in the range 600 to 1400 F because the thermal treatments involved during welding add to carbon's ability to precipitate as intergranular graphite. This weakens the microstructure. The remedy is to limit the carbon content to below 0. 02 per cent. In the chromium-bearing nickel-base alloys carbon in normal amounts causes no problems.

Molybdenum - Molybdenum in the amount of 20 to 30 per cent in two-phase alloys causes weld hot cracking. Single-phase alloys do not crack seriously. Thus, only one or two of the important alloys should cause concern attributable directly to molybdenum.

Silicon - Silicon causes weld hot cracking in nickel-base alloys. The severity of this effect is quite variable, depending both upon the alloy and the welding process used. It is especially bad in high-nickel chromium-bearing alloys. Columbium is often added to high-nickel alloys to counteract the effects of silicon.

Aluminum - Aluminum is added to nickel alloys as a deoxidizer and to develop age-hardening properties. In general, aluminum has the same effect on welding as silicon. The usefulness of aluminum as an age hardener in high-temperature high-nickel alloys makes it a desirable addition to filler metals for these alloys. Usually, however, hot-cracking problems arise before the full benefit of the aluminum is obtained. Thus, other means must be found to match weld-metal properties with base-metal properties.

Titanium - Titanium is added to high-nickel alloys for two reasons; to develop age-hardening response and to reduce gas porosity. The effect of titanium when welding these alloys is very much like that of aluminum. The weld metal becomes hot-short and crack-free welds become hard to obtain, especially in restrained joints.

It must be remembered that many factors, in addition to composition, such as prior thermal and mechanical treatments, grain size, cleanliness, and joint design all will affect the final properties of the welded joint.

Some alloying elements have a considerable effect in joining operations other than fusion welding, such as brazing. With other alloying elements the effect is small. The most important consideration in brazing after the proper choice of brazing filler metal is what surface contaminants are produced by the alloying elements. Nickel-base alloys containing aluminum and/or titanium require special consideration for successful brazing. This will be discussed later in this report.

JOINT DESIGN

The establishment of universally suitable joint designs for use with nickel-base alloys is impossible. This is because of the wide variety of different applications in which these alloys are useful and to the intricate designs often involved. Some generalizations are possible, however. These are:

(1) Avoid corner joints

(2) Use full penetration joints to avoid notch effects because nickel alloys are not very fluid.

(3) Use joints with wide openings (see Figure 1).[4]

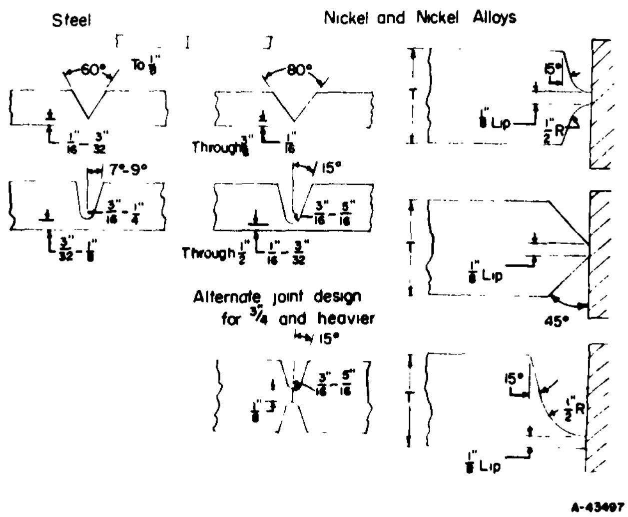


FIGURE 1. COMPARISON OF JOINT DESIGN (STEEL VERSUS NICKEL ALLOYS)[4]

For high-temperature applications, stress-rupture properties may be more useful than other properties for design purposes. Elevated-temperature weld-joint efficiencies provide a better assessment of high-temperature-alloy weldment properties than do room-temperature properties. Stress-rupture data are plotted for Inconel weldments in Figure 2.[5] These data indicate that up to 1400 F, 100 per cent joint efficiencies are obtained for all rupture lives. At 1600 F, and above, joint efficiencies degenerate. The effect of the grain size of the base plate is also indicated. In general, welds in fine-grained Inconel are more efficient than those in coarse-grained material. Postwelding heat treatments improve the rupture life at 1800 F and at high stress levels.

The strength-temperature relationship of cast versus wrought nickel-base alloys based on short-time tensile properties is shown in Figure 3.[6] As-welded structures contain cast material and are usually weaker.

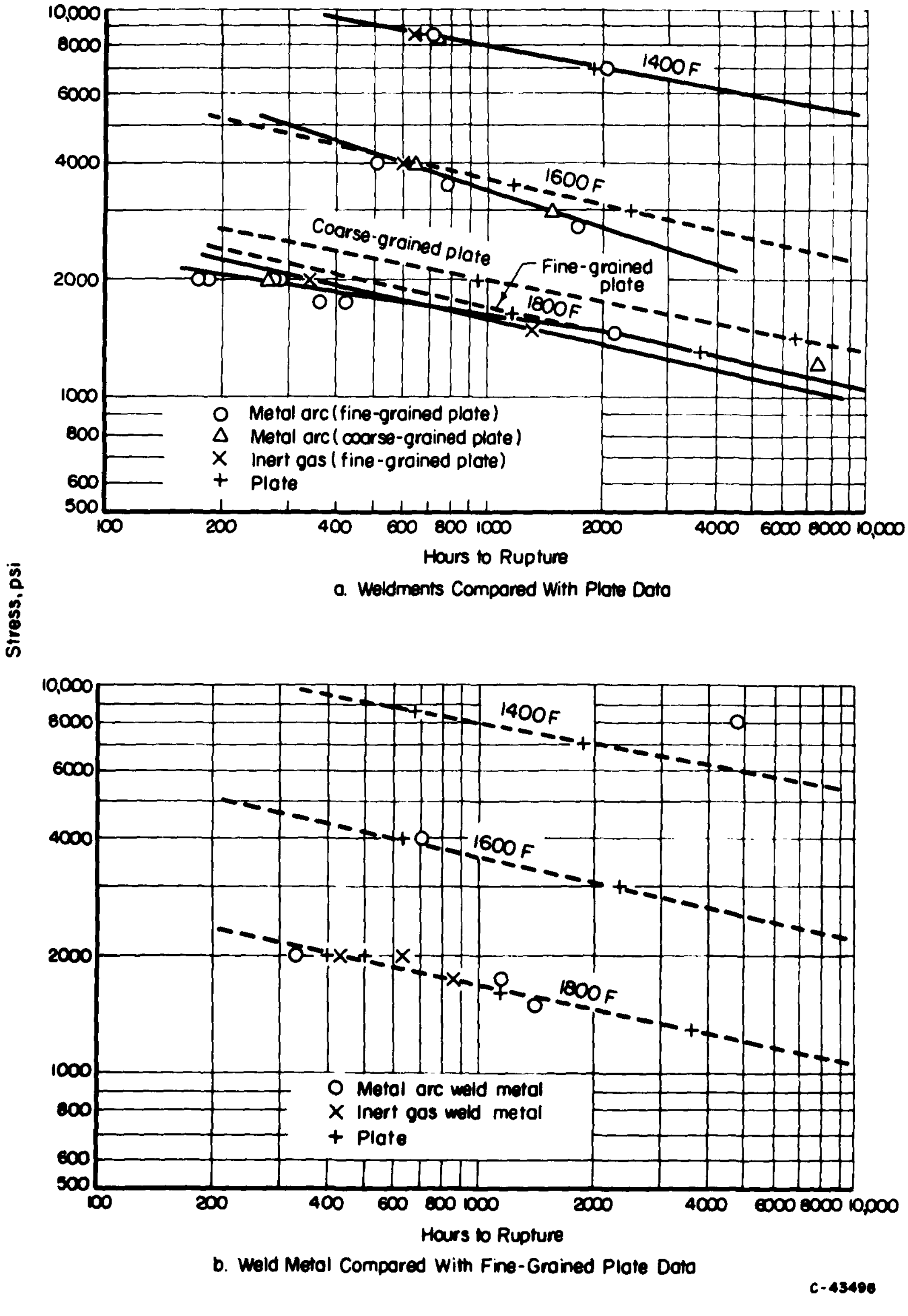


FIGURE 2. STRESS-RUPTURE DATA FOR INCONEL WELDMENTS[5]

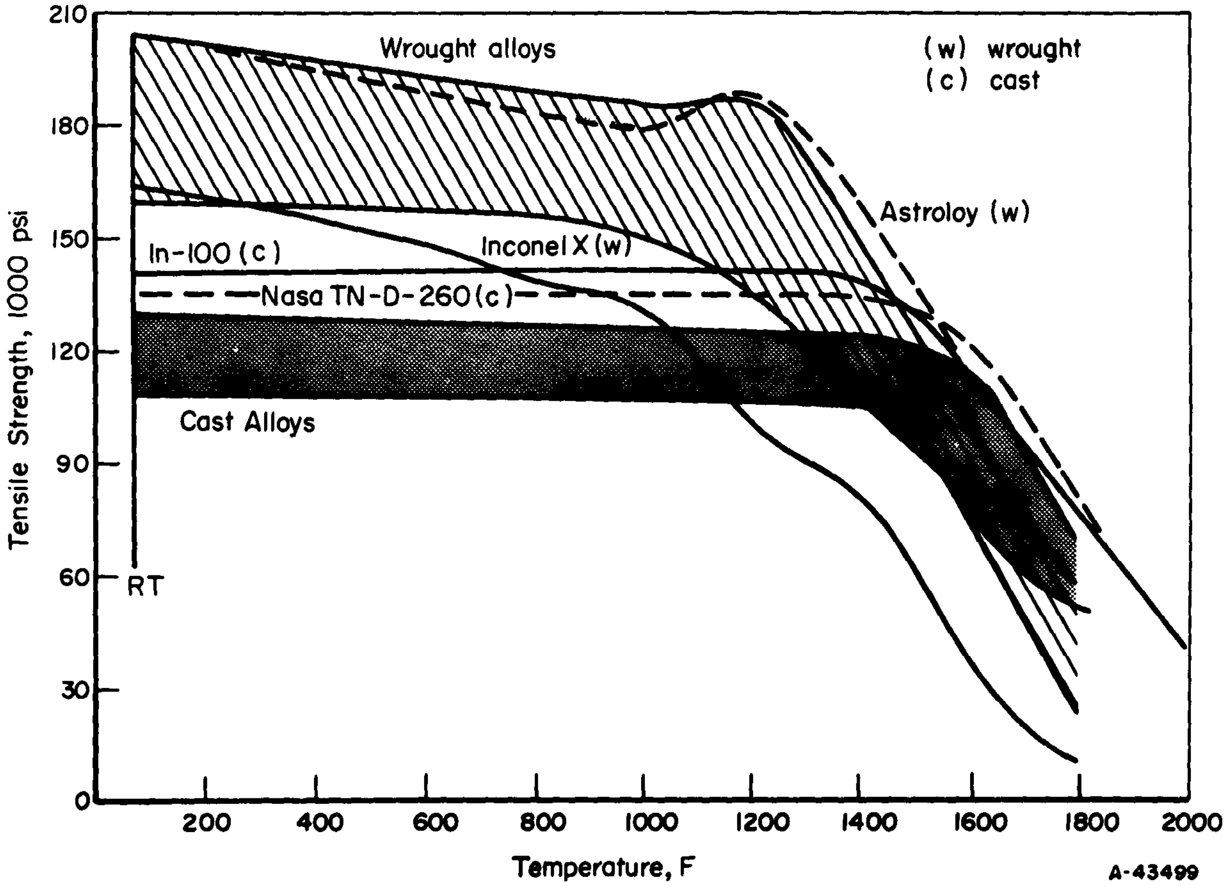


FIGURE 3. STRENGTH STABILITY OF SUPERALLOYS (NICKEL BASE)(6)

ALLOYS HARDENED PRINCIPALLY BY SOLID SOLUTION

Included in this group are the older, less-heat-resistant but highly corrosion-resistant nickel-base alloys and pure nickel (see Table 1). These alloys are not usually considered heat treatable. Also included are alloys which are heat treated to different property levels by solid-solution strengthening.

Monel, Inconel, Nimonic 75, and Illium Alloys

Fusion Welding

The alloys can be welded by all the processes normally used for steel. Procedural differences are necessary, however. Both submerged-arc welding and CO_2-shielded welding processes produce inferior joints in high-nickel alloys.

Alloys such as Inconel, the Illiums, and Monel do not harden when quenched from an elevated temperature; therefore, it is not necessary to preheat before welding. In fact, preheating is often considered harmful. These alloys should be welded in the annealed condition to avoid cracking in the parent metal. Cracks result from a lack of ductility in certain temperature ranges during cooling from welding temperature.

When welding alloys like Monel and Inconel, starting tabs and stringer beads should be used. The heat input should be kept at a minimum and the interpass temperature as low as possible.

Lack of attention to several basic precautions will cause innumerable problems. Shop dirt of all types must be kept out of the weld. The alloys should be cleaned of oil, grease, crayon, etc., before welding. Oxides should also be removed before welding. The joint designs should take into consideration that nickel alloys are not as fluid as steel. Interpass cleaning is important to obtain sound welds. The nickel-base alloys should always be welded in the annealed condition if possible.

Minga and Richardson(7) reported on the fabrication of corrosion-resistant components from Inconel for use in nuclear-power applications. A short review of their work will indicate the requirements which must be met to make nuclear-quality welds. Such welds must have the highest possible integrity, both with respect to corrosion resistance and mechanical properties. To obtain such integrity, they report that strict control of the following variables is mandatory.

(1) Choice of welding process

(2) Filler-wire surface condition and composition

(3) Welding line voltages

(4) Joint design

(5) Welding technique

(6) Operator skill

(7) Welding fixtures

(8) Equipment condition

(9) Shielding gas.

If such variables are not carefully controlled, problems will arise from: (1) fissuring and hot cracking, (2) inclusions, (3) cold laps, and (4) porosity.

Fissuring and hot cracking may be different degrees of the same problem. They can be overcome by using proper welding procedures and techniques. For example, Minga and Richardson found that sound welds in heavy sections were hard to produce with fully automatic gas metal-arc welding using stringer beads. Sound welds were made semiautomatically by using a weaving technique which gave a more favorable solidification pattern.

Ineffective gas shielding is the usual cause of inclusions. Maintaining proper gas flow rates, eliminating excessive drafts, preventing gas and water leaks, and choosing proper nozzle size to keep the weld pool covered will aid in their elimination. Weaving techniques designed to float out oxides also help.

Porosity is usually attributed to foreign material such as oil or water in the weld area or to improper shielding. Proper cleaning will eliminate the former. The latter is more troublesome. Air may be aspirated into the weld either by instability of the arc or by too great a gas flow. Too little gas flow for the equipment being used will also cause porosity.

The past few paragraphs point to the requirements and methods of meeting them for heavy sections of Inconel. The same basic requirements and methods control are necessary when welding lighter sections of Inconel and other nickel-base alloys.

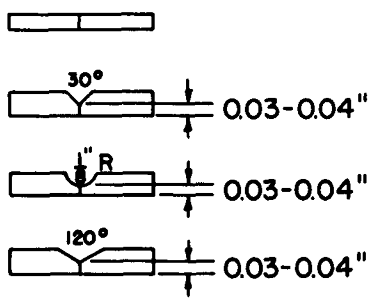
O'Connell, et al.,[8] report on the fabrication of a Monel heat exchanger with fins made from corrugated 0.050 inch Monel sheet. The most important single factor in their success was cleanliness. All welding was done in an air-conditioned room free from normal shop dirt.

Initially, the sheet Monel was welded without adding filler metal. Failures occurred in these welds because of stress corrosion in areas of microporosity resulting from the lack of deoxidizers in the Monel. The use of filler metal on one pass eliminated microporosity. Another cause of failures was lack of penetration. This was eliminated by improving the underside weld shielding and employing a weaving technique to assure complete penetration. The resultant Monel sheet subassembly was also stress relieved in a reducing atmosphere for 1 hour at 1000 F.

Dickinson and Watkins[9] have discussed the welding of Inconel and Monel in chemical-processing plants. The manual metal-arc welding procedures recommended for the available filler metals were not satisfactory for Inconel. Changing to another filler metal gave consistently good welds. The unsatisfactory results were obtained with Inconel 132-type filler rod; the best results came with BP24 type rod. The difference between these electrodes was not given.

When welding Monel piping having wall thicknesses between 0.08 and 0.125 inch, several problems were encountered by Dickinson and Watkins. They purged air from the piping with inert gas to prevent oxidation, and used argon-arc rather than metal-arc methods to control penetration. A special deoxidized filler wire, Monel 60, added to insure a weld pool containing approximately 50 per cent filler eliminated porosity. The joint designs used are shown in Figure 4. These authors also found that nitrogen was just as effective as argon in promoting a smooth oxidation-free internal (underside) bead surface. Nitrogen did not alter the mechanical or corrosion properties of the Monel. Nitrogen was usable only with tight fitup. Poor fitting joints permitted nitrogen to enter the arc area and cause porosity.

Nominal Inside Diameter, in.	Wall Thickness, in.	Preparation
1	0.080	
2	0.104	
3	0.128	
3 *	0.128	



* For use where J-type machining was not possible.

A-43500

FIGURE 4. PREPARATION FOR MONEL-PIPE BUTT JOINTS[9]

Resistance Welding

Published information on the welding of nickel and nickel alloys by resistance methods is not plentiful. One comprehensive bulletin[10] covers all resistance-welding processes applicable to many of the more common nickel-base alloys. This bulletin should be consulted by those not experienced with nickel-base alloys. Parts of some of the tables given are reproduced as Tables 3 and 4.

North American[11] has published spot-weld shear design values for Inconel (see Figure 5). Waller and Knowlson[12] have developed the welding conditions for spot welding Nimonic 75 and studied the effect of postweld heat treatments on the mechanical properties. Such treatments did not improve the shear strength. Spot welding does not change the stress-rupture strength of Nimonic 75 at elevated temperatures.

Brazing

Brazing of nickel-base alloys of the simpler solid-solution-strengthening type poses little problem, provided the proper brazing alloy is chosen for the proposed

TABLE 3. RECOMMENDED CONDITIONS FOR SPOT WELDING ANNEALED NONAGING NICKEL-BASE ALLOY SHEET

(Adapted from International Nickel Co., Inc., Technical Bulletin T-33)[10]

Thickness, in.	Electrode Diameter, in.		Electrode Force, lb	Weld Time, cycles	Weld Current, amp	Minimum Contact Overlap, in.	Minimum Weld Spacing, in.	Diameter of Fused Zone, in.	Average Shear Strength, lb	Minimum Shear Strength, lb
	Top	Bottom								
					Nickel					
0.005 to										
0.005	5/32	5/32	100	3	7,100	1/4	3/8	0.10	40	30
0.125	5/32	3/16	115	3	8,200	1/4	5/8	0.10	68	55
0.010 to										
0.010	3/16	3/16	130	3	11,800	1/4	3/8	0.12	170	135
0.125	5/32	3/16	150	3	12,500	1/4	5/8	0.12	260	210
0.015 to										
0.015	3/16	3/16	250	3	12,300	1/4	7/16	0.12	225	180
0.125	3/16	5/8	260	3	13,100	1/4	5/8	0.13	390	310
0.021 to										
0.021	5/32	5/32	370	4	7,800	5/16	9/16	0.12	440	350
0.125	5/32	5/8	380	4	9,000	5/16	3/4	0.13	566	450
0.031 to										
0.031	3/16	3/16	900	4	15,400	3/8	7/8	0.18	950	760
0.125	3/16	5/8	980	6	14,200	3/8	1	0.18	1160	930
0.063 to										
0.063	1/4	1/4	1720	6	21,600	5/8	1-1/2	0.25	3000	2400
0.125	1/4	1/4	1800	10	21,000	5/8	1-3/4	0.25	3316	2650
0.125 to										
0.125	3/8	3/8	3300	20	31,000	7/8	2-1/4	0.37	7000	5600
					Monel					
0.005 to										
0.005	5/32	5/32	220	2	5,000	1/4	1/4	0.10	70	55
0.125	5/32	5/8	250	4	8,700	1/4	1/2	0.11	108	85
0.010 to										
0.010	5/32	5/32	270	2	7,200	1/4	1/4	0.12	180	145
0.125	5/32	5/8	325	4	9,900	1/4	1/2	0.14	276	220
0.015 to										
0.015	3/16	3/16	300	2	8,600	1/4	5/16	0.13	310	250
0.125	3/16	5/8	325	8	9,500	1/4	1/2	0.14	456	365
0.021 to										
0.021	3/16	3/16	300	12	6,200	5/16	7/16	0.13	560	450
0.125	3/16	3/8	325	12	8,200	3/8	9/16	0.14	692	550
0.031 to										
0.031	3/16	3/16	700	12	10,500	3/8	5/8	0.17	1056	845
0.125	3/16	5/8	775	12	11,800	1/2	3/4	0.19	1348	1075
0.063 to										
0.063	5/16	5/16	2700	12	15,300	5/8	1-1/8	0.31	2584	2060
0.125	5/16	5/8	2700	12	16,200	5/8	1-1/4	0.32	2944	2360
0.125 to										
0.125	1/2	1/2	5000	30	30,000	7/8	1-5/8	0.47	7300	5850

TABLE 3. (Continued)

Thickness, in.	Electrode Diameter, in. Top	Electrode Diameter, in. Bottom	Electrode Force, lb	Weld Time, cycles	Weld Current, amp	Minimum Contact Overlap, in.	Minimum Weld Spacing, in.	Diameter of Fused Zone, in.	Average Shear Strength, lb	Minimum Shear Strength, lb
					Inconel					
0.005 to										
0.005	5/32	5/32	300	2	7,000	1/4	1/4	0.11	90	70
0.125	5/32[a]	5/8	325	6	5,600	1/4	3/8	0.15	160	130
0.010 to										
0.010	3/16	3/16	320	4	7,500	1/4	1/4	0.12	220	175
0.125	5/32[a]	5/8	400	6	4,600	1/4	3/8	0.14	365	370
0.015 to										
0.015	3/16	3/16	360	6	7,600	1/4	1/4	0.12	370	295
0.125	3/16	5/8	400	12	4,600	1/4	3/8	0.16	700	560
0.021 to										
0.021	5/32	5/32	300	12	4,000	5/16	7/16	0.12	680	545
0.125	3/16[a]	5/8	550	12	6,300	5/16	1/2	0.15	860	690
0.031 to										
0.031	3/16	3/16	700	12	6,700	3/8	9/16	0.18	1150	920
0.125	1/4[a]	5/8	750	12	8,500	3/8	3/4	0.20	1510	1210
0.063 to										
0.063	5/16	5/16	2070	12	12,000	5/8	1-1/8	0.31	3450	2750
0.125	5/16	5/8	2600	20	12,000	5/8	1-1/4	0.32	3530	3820
0.125 to										
0.125	7/16	7/16	5270	30	20,100	7/8	1-5/16	0.44	8000	6400

(a) Indicates molybdenum-tipped electrode.

Notes:

(1) Material should be free from scale, oxides, paint, grease, and oil.

(2) Electrode shape may be flat rather than domed, in which case the shear strengths and nugget diameters will be higher and larger than shown in the table.

(3) Electrode Materials

Electrode Materials	Class II	or Class III	or Molybdenum Faced
Minimum Conductivity	80% Cu	75% Cu	33% Cu
Minimum Hardness	68 R_B	75 R_B	83 R_B

(4) Minimum weld spacing is that spacing for two pieces for which no special precautions need be taken to compensate for shunted current effect of adjacent welds. For three pieces increase spacing 30 per cent.

TABLE 4. RECOMMENDED CONDITIONS FOR FLASH WELDING NICKEL-ALLOY RODS[10]

Material	Rod Diam, in.	End Preparation[a]	Flashing Distance, in.	Flashing Time, sec	Current Duration During Upset, cycles	Upset Distance, in.	Watt-Hours/Weld	Weld Strength, psi	Rod Strength, psi
Nickel	1/4	Pointed	0.442	2.5	1.5	0.125	2.15	58,000	65,100
Nickel	3/8	Pointed	0.442	2.5	2.5	0.145	4.87	65,600	66,500
Monel	1/4	Pointed	0.442	2.5	1.5	0.125	1.93	68,500	70,500
Monel	3/8	Pointed	0.442	2.5	2.5	0.145	5.55	80,300	84,700
K Monel	1/4	Pointed	0.442	2.5	1.5	0.125	2.02	93,900	100,000
K Monel	3/8	Pointed	0.442	2.5	2.5	0.145	4.79	98,800	99,000
Inconel	1/4	Pointed	0.442	2.5	1.5	0.125	2.15	101,200	109,800
Inconel	3/8	Pointed	0.442	2.5	2.5	0.145	5.19	102,000	106,000

(a) 110-degree included angle.

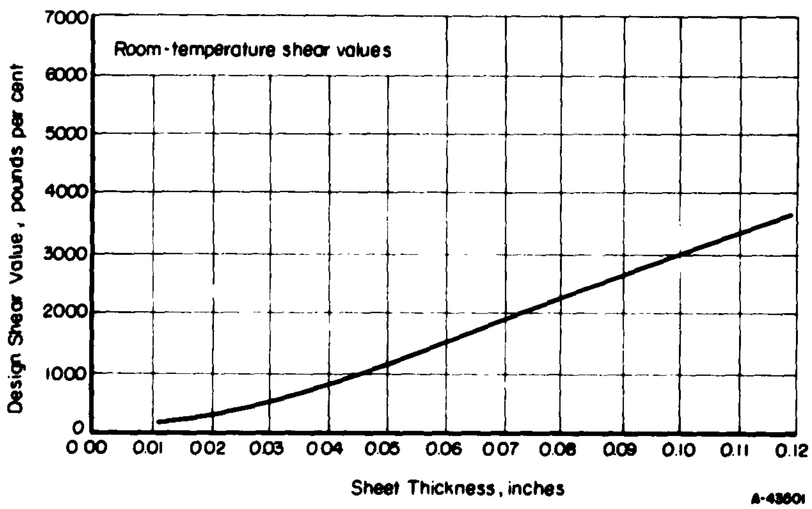


FIGURE 5. SPOT-WELD SHEAR DESIGN VALUES FOR TWO-SHEET COMBINATIONS[11] OF INCONEL

application. It is necessary to know if the brazing alloy can be used in the corrosive medium encountered. With alloys that are not heat treatable, there should be little worry with the compatibility of the brazing thermal cycle and the base-metal properties. The brazing operation will at least partially anneal these alloys. All nickel-base alloys should be free of stress, internal or applied, when being brazed with silver alloys. Nickel alloys are subject to stress-corrosion cracking when in contact with molten silver or silver alloys. Copper and the nickel-base high-temperature brazing filler metals can also be used.

When it is desirable to braze these alloys with nickel-base brazing filler metals, it should be remembered that detrimental base metal-filler metal interactions may occur during brazing. This subject is discussed in a later section on the brazing of age-hardenable nickel-base alloys.

Hastelloy Alloys

Fusion Welding

The more complex solid-solution-strengthened alloys can be fusion welded by most of the commonly used processes. Successful welding depends on maintaining the proper welding procedures and on having the alloy in the proper metallurgical condition. These alloys are subject to hot shortness in the temperature range 1200 to 1800 F. This hot-short range is shown in Figure 6 for Hastelloy B[13]. These alloys are also subject to precipitation of carbides which lower their corrosion resistance. Consequently, heating during welding should be kept at a minimum and the welding time as short as possible. Four basic principles are given[14] for successful welding: (1) have minimum weld restraint, (2) keep wrought base material as cool as possible when welding, (3) provide good joint alignment, and (4) use stringer beads.

Cleanliness is very important when welding the more complex solid-solution strengthening alloys, as is the case for all nickel-base alloys. Oil, grease, and all other foreign matter should be removed from the joint area before welding.

Slaughter, Patriarca, and Clausing[15] made a study of the properties of welds in Hastelloy B, W, and N (INOR-8) plate 0.5 inch thick. The objective was to determine the relative weldability and the effect of aging at 1200 F on the mechanical properties of the weld metal. The welding conditions and joint type are shown in Figure 7. The square butt joint was used in order to get good all-weld-metal test specimens. The filler metals were the same composition as the base metal. The weldment was restrained to minimize warpage.

It was concluded that these alloys are readily weldable if the restraint is not high. With qualified welders no cracking or porosity problems should be expected. It is suspected that the restraint during these studies was not great enough to cause cracking. The effect of aging at 1200 F on the ductility, as measured by Vickers hardness, of the three alloys studied is shown in Figure 8. The resistance of Hastelloy N to loss of ductility at 1200 F is quite dramatic.

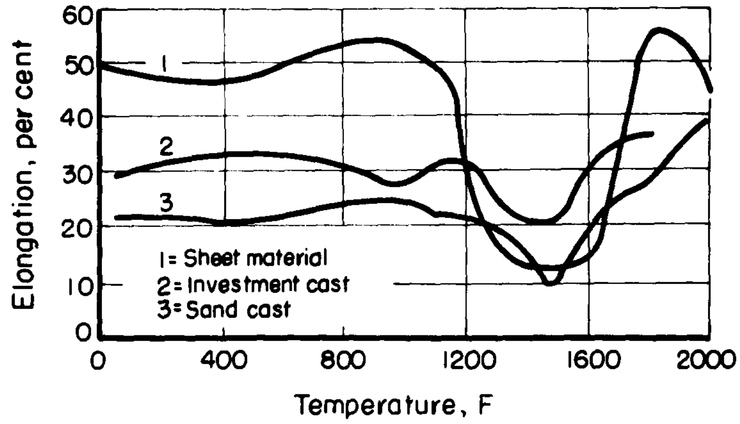
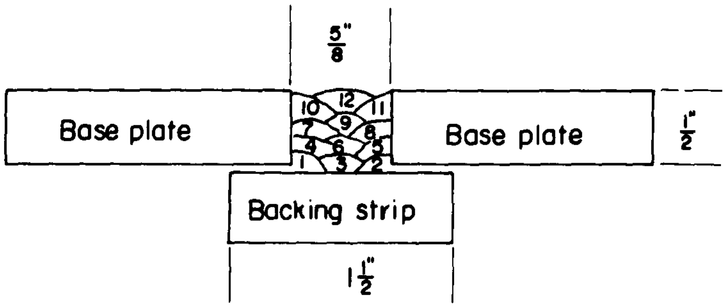


FIGURE 6. THE EFFECT OF TEMPERATURE ON THE DUCTILITY OF HASTELLOY B[13]



Welding Conditions

Pass Number (Stringer Type)	Welding process	Filler wire diam in.	Current DCSP, amp
1	Inert arc	3/32	140
2	Inert arc	3/32	140
3-12	Inert arc	1/8	170

Welding Speed - 2.5 ipm (approx)

A-43502

FIGURE 7. WELDING SEQUENCE FOR TEST PLATES[15]

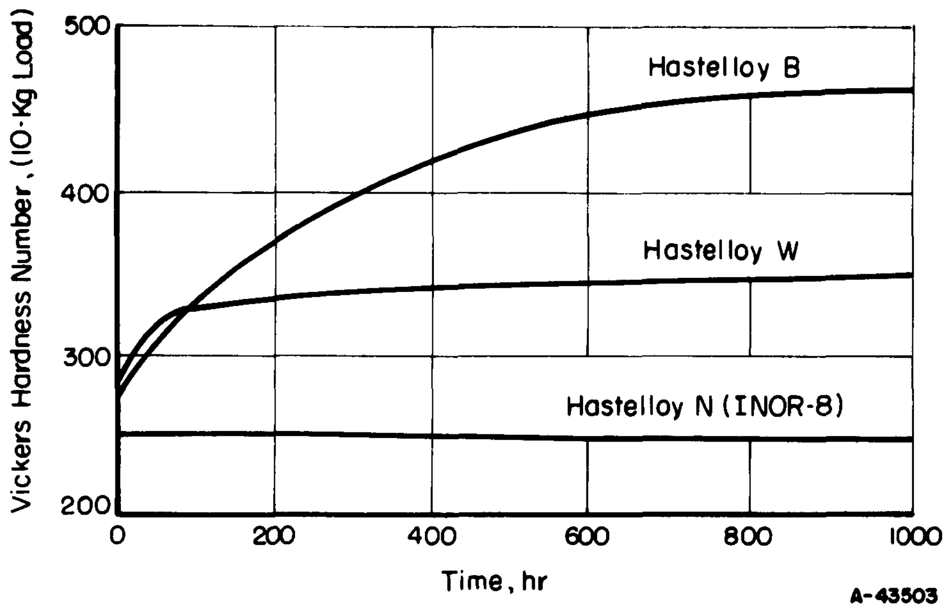


FIGURE 8. EFFECT OF AGING TIME AT 1200 F ON ROOM-TEMPERATURE HARDNESS OF WELD METALS[15]

Studies on the inert-gas shielded-arc welding of Hastelloy X sheet are reported by Perriton and Phillips[13]. The data in Table 5 are for butt joints; essentially the same conditions were used for corner and fillet joints. A grooved copper backup bar was used during welding. The authors comment that the corners of the backup bar should be rounded to promote good weld contour and heat transfer. The inert-gas-shielded tungsten-arc process was not recommended for sheet thicknesses over 0. 125 inch. This is because the heat input into the base metal is excessive.

TABLE 5. ARGON-SHIELDED TUNGSTEN-ARC WELDING CONDITIONS FOR FOR HASTELLOY X[13]

Base-Metal Thickness, in.	Number of Passes	Current Downhand Welding, amp	Tungsten-Electrode Diameter, in.	Filler-Rod Diameter, in	Argon Flow, cu ft/hr
0. 063	1	60-90	1/16, 3/32	1/16, 3/32	20-40
0. 093	1-2	100-125	3/32	1/16, 3/32, 1/8	20-40
0. 125	1-2	100-125	3/32	1/16, 3/32, 1/8	20-40

Beemer and Mattek[16] have reported on the fusion welding of thin-gage Hastelloy X. Welding conditions were developed for inert-gas tungsten-arc welding this alloy in 0. 005-, 0. 010-, and 0. 040-inch thicknesses. Three-piece T-sections were welded to

simulate production problems. Their study also included René 41 in the same thicknesses. Two tables from their work are reproduced here as Tables 6 and 7. As in the case of all other investigators, Beemer and Mattek emphasize cleaning, joint preparation, and precision welding. This reference should be consulted by anyone concerned with the fusion welding of Hastelloy X in thicknesses of 0. 040 inch or less.

Boeing(17) studied both mechanized and manual butt fusion welds in Hastelloy X. Cleaning before welding was stringent; involving filing, sanding, and wiping with clean gauze soaked in methyl ethyl ketone immediately before welding. Copper hold-down bars and backup bars grooved for inert-gas purging of the underside of the joints were used. The schedule best suited for manual welding butt joints in 0. 040 material was:

Arc Voltage	10 v
Current	50 amp
Torch speed	2. 66 ipm
Wire Diameter	0. 045 in.

The schedules that produced satisfactory butt welds when using mechanized equipment are given in Table 8. Mechanical properties are given in Table 9. Close control of weld variables and proper processing techniques were considered a must to insure sound weldments.

Boeing also has reported on the lap fusion welding of Hastelloy X. Schedules which gave good welds in 0. 040-inch to 0. 040-inch lap joints were as follows.

	Weld Current		Torch Speed,	Torch Gas		Backup Gas		Wire Feed,
Type Weld	Amp	Volts	ipm	Type	Cfh	Type	Cfh	ipm
Mechanized	72	11. 5	10	Helium	90	Argon	10	None
Manual	54	8. 5	6	Argon	11	Argon	4	3. 0

On lap fusion welds, complete penetration of the bottom sheet was required for strength and consistency. A gridded copper backup plate was used when making the full-penetration welds.

Hastelloy W is unique among the solid-solution-hardening alloys. It was developed as a filler metal for welding other metals to nickel-base alloys. In this role, it has proven very useful, having been used for welding nickel-base alloys, cobalt-base alloys, and stainless steels. Hastelloy W provides an ideal matrix for welding a number of dissimilar metals.

Resistance Welding

The more complex solid-solution-strengthening nickel-base alloys can all be resistance welded by the usual methods; spot, seam, and flash welding. Spot and seam

TABLE 6. MECHANICAL PROPERTIES AND WELD SCHEDULES OF SOLUTION-HEAT-TREATED AND BUTT-WELDED FOIL GAGE MATERIAL[16]

Test	Material	Gage[a], in.	Testing to Rolling Direction[b]	Yield Strength, psi	Ultimate Strength, psi	Elongation in 2 In., %	Location of Fracture[c]	Weld Efficiency[d], %	Loss of Elongation[e], %	180-Deg Bend Over 1T[f]
1	René 41	0.005	Parallel	78,300	129,300	20.3	HA	93.5	40.0	No cracks
2	René 41	0.005	Transverse	74,300	114,809	16.3	P & HA	83.0	48.0	No cracks
3	René 41	0.010	Parallel	85,766	131,600	29.5	W	97.5	34.2	No cracks
4	René 41	0.010	Transverse	69,000	129,500	27.5	W	96.5	33.2	No cracks
5	Hastelloy X	0.005	Parallel	62,270	97,030	8.2	HA	80.2	70.4	No cracks
6	Hastelloy X	0.005	Transverse	63,870	108,530	24.0	HA, P, W	90.8	10.4	No cracks
7	Hastelloy X	0.010	Parallel	53,170	120,430	33.8	P	100.0	14.4	Slight cracking
8	Hastelloy X	0.010	Transverse	53,270	105,300	21.5	P	93.3	41.4	No cracks

Welding Schedule

Test	Speed, ipm	Current, amp	Arc, volts	Argon, cfh Shielding	Argon, cfh Backing
1	6	4	2	8	8
2	6	4	2	8	8
3	6	9	2	12	12
4	6	9	2	12	12
5	6	4	2	8	8
6	6	4	2	8	8
7	6	9	2	12	12
8	6	9	2	12	12

(a) Coupons ground flush at welds.
(b) Welds 90 deg to testing direction.
(c) HA - heat-affected zone; P - base metal; W - weld.
(d) Per cent weld efficiency = [ultimate psi (weld coupon) x 100] [ultimate psi (base-metal coupon)].
(e) Per cent loss of elongation = [per cent elong. base metal - per cent elong. weld coupon x 100] (per cent elongation base metal).
(f) Face and root bends were made with axis of bend parallel to weld direction; radiographs of all samples were acceptable.

TABLE 7. MECHANICAL PROPERTIES AND WELD SCHEDULES OF SOLUTION-HEAT-TREATED AND BUTT-WELDED 0.040 INCH MATERIAL[16]

Test	Material	Filler-Metal Diameter[a], in.	Testing to Rolling Direction[b]	Yield Strength, psi	Ultimate Strength, psi	Elongation in 2 In., %	Location of Fracture[c]	Weld Efficiency[d], %	Loss of Elongation[e], %	180-Deg Bend Over 2T[f]
9	René 41	0.040	Parallel	77,230	132,890	26.2	W	93.9	39.5	Slight cracking
10	René 41	0.040	Transverse	74,030	125,750	19.3	W	89.5	48.3	Slight cracking
11	René 41	None	Parallel	77,070	132,490	23.2	W	93.7	46.3	Slight cracking
12	Hastelloy X	0.040	Parallel	59,920	115,010	38.8	P	100.0	7.0	Slight cracking
13	Hastelloy X	0.040	Transverse	59,790	109,860	23.2	W	96.6	40.8	Slight cracking
14	Hastelloy X	None	Parallel	60,550	112,410	28.8	W	99.4	30.9	Slight cracking (face)
15	Hastelloy X	0.040	Parallel	63,320	113,580	34.7	P, W	100.0	16.8	Heavy cracking (face)
16	Hastelloy X	0.040	Transverse	59,020	114,310	33.3	P, W	100.0	15.1	Heavy cracking root

Welding Schedule

Test	Speed, ipm	Current, amp	Arc, volts	Argon, cfh Shielding	Argon, cfh Backing	Wire Speed, ipm
9	8	45	8	17	8	7
10	10	45	8	16[g]	20	10
11	13	45	8	18	12	--
12	10	45	8	16	15	14
13	10	45	12	16[g]	15	14
14	12	30	8	15[g]	5	--
15	15	55	8	18	8	16
16	15	55	8	18	8	17-1/2

(a) Filler metal of same material welded except in Tests 15 and 16 where Hastelloy W wire was used.
(b) Welds 90 deg to testing direction.
(c) W – weld; P – base metal.
(d) Per cent weld efficiency = [ultimate psi (weld coupon) x 100] [ultimate psi (base-metal coupon)].
(e) Per cent loss of elongation = [per cent elongation base metal – per cent elongation weld coupon x 100] (per cent elongation base metal).
(f) Face and root bends were made with axis of bend parallel to weld direction; radiographs of all samples were acceptable.
(g) Plus 10 cfh helium gas.

TABLE 8. SCHEDULE FOR MECHANIZED FUSION BUTT WELDING OF HASTELLOY X[17]

Gage Combination, inch	Weld Current		Torch Speed, ipm	Torch Gas		Backup Gas		Holddown Spacing, inch	Backup Groove	
	Amperes	Volts		Type	Cfm	Type	Cfm		Width, inch	Depth, inch
0.010 to 0.010	15	8	17.5	Argon	30	Argon	7.5	0.10	0.010	0.007
0.020 to 0.020	30	7.5	20	Argon	35	Argon	7.5	0.18	0.130	0.010
0.040 to 0.040	53	7	10	Argon	30	Argon	5.0	0.20	0.200	0.030

TABLE 9. MECHANICAL PROPERTIES OF MECHANIZED FUSION BUTT WELDS IN HASTELLOY X[17]

(0.040-inch sheet to 0.040-inch sheet)[a]

Type of Test	Filler Wire	Yield Strength, psi	Ultimate Strength, psi	Elongation in Indicated Inches, per cent			Bendability[b]	Failure Location
				0.5	1.0	2.0		
Joint, tensile	None	65,000	112,900	32	29	26	0.5	Center of weld
Weld metal, tensile[c]	None	66,300	107,400	27	22	18	0.5	Center of weld
Joint, tensile	Yes	63,000	113,700	57	46	38	0.5	Base metal
Weld metal, tensile[c]	Yes	63,400	101,700	24	20	17	0.5	Center of weld

(a) Average value of nine specimens for each type of weld.
(b) Ratio of minimum punch radius to material thickness bent without cracking.
(c) Specimen prepared to cause failure in weld metal by removing reinforcement and reducing section.

welding of these alloys in sheet form has become relatively common in recent years. Correct surface preparation and strict attention to the control of welding variables is mandatory for reproducible results. This is illustrated by the following exerpt in the Boeing work on Hastelloy X. "In resistance-spot welding operations, the use of oscillographic spot weld analyzing equipment is necessary during equipment qualification, weld schedule certification, and in-process quality control checks to insure that proper machine settings are being used. Accurate adjustment and control of all variables must be maintained. For example, when using a welding schedule requiring five cycles it was found that a phase shift control of 33 per cent of the available amperage gave good welds with no spitting. A shift control setting of 32 per cent gave insufficient fusion and a setting of 35 per cent gave excessive fusion or spitting". These investigators could see little difference in the requirements for producing successful spot welds in Hastelloy X, a solid-solution-strengthening nickel-base alloy; René 41, a precipitation hardening nickel-base alloy; or HS 25, a cobalt-base alloy. All of these alloys were very susceptible to cracking, forge out, and expulsion of molten metal. Approximate spot-welding schedules applicable to these alloys are given in Table 10. These parameters produced acceptable welds except when a portion of the weld pressure was used to force mismatched parts into alignment. Good fit up is mandatory if highly controlled welding variables are to be useful.

TABLE 10. APPROXIMATE SPOT-WELDING SCHEDULES FOR HASTELLOY X, RENÉ 41, AND HS 25[17]

Gage Combination, inch	Weld Variables			Forge	Postheat Variables			Cool Time, cycles
	Pressure, lb	Current, amperes	Time, cycles	Pressure, lb	Time, cycles	Number of Impulses	Current, amperes	
0.010 to 0.010	530	15,000	4	1150	4	3	900	0.5
0.020 to 0.020	810	15,300	7	1580	7	5	1350	0.5
0.040 to 0.040	1250	11,700	9	3400	9	4	2700	0.5
0.010 to 0.020	600	12,150	6	1750	6	6	3150	0.5
0.040 to 0.040 to 0.040	1330	19,800	10	4450	10	3	4050	0.5

Beemer and Mattek[16] also give the welding parameters for resistance spot welding thin-gage Hastelloy X and René 41. The data are not directly comparable but are reproduced here (Table 11) for the sake of completeness.

Brazing

The chief criteria for successful brazing of the Hastelloy alloys are: (1) thorough cleaning and maintenance of cleanliness, (2) proper brazing alloy choice for intended application, (3) freedom from restraint of any kind during brazing, (4) short heating cycles to prevent aging, (5) fast cooling, but not quenching.

TABLE 11. RESISTANCE-SPOT-WELD TENSILE SHEAR, NUGGET SIZE, AND WELD SCHEDULES[16]

Material and Thickness, in.	No. of Coupons	Shear Strength, in-lb			Avg Nugget Diameter, in.	Avg Penetration, %	Weld Schedule							Electrode RWMA Class II
		Avg	Min	Range			Preheat, %	Weld and Temper, %		Squeeze, cycles	Hold, cycles	Force	Phase A	
René 41, .005 to .005	15	58	40	30	0.044	60	10[a]	10[a]	10[a]	20	20	93		5/8-in. diam 4-in. face radius
René 41, .005 to .010	15	44	30	20	0.034	1	--	15[a]	--	27	7	151	Off	5/8-in. diam 4-in. face radius
Hastelloy X, .005 to .005	15	44	40	10	0.047	36	--	10[a]	--	27	--	134	Off	1/2-in. diam 4-in. face radius
Hastelloy X, .005 to .010	15	41	35	10	0.062	38	--	10[a]	--	27	7	134	Off	1/2-in. diam 4-in. face radius
René 41, .040 to .040	15	2196	2035	275	0.190	40	38[b]	51[c]	45[e]	4	--	2000		5/8-in. diam 5-in. face radius
Hastelloy X, .040 to .040	16	2095	2000	200	0.22	48	38[b]	41[d]	52[f]	4	2	2000		5/8-in. diam 5-in. face radius

	Interface	Pulse	Interval
(a)	1	1	1
(b)	1	7	7
(c)	3	7	7
(d)	5	10	7
(e)	2	1	8
(f)	2	3	8

When brazing these alloys for elevated-temperature use with the standard nickel-base brazing filler metals, intergranular penetration and solution of the base metal may become a problem. This is discussed under the brazing of age-hardenable nick .i-base alloys.

ALLOYS CAPABLE OF PRECIPITATION HARDENING

The need for alloys which can stand high stresses at high temperatures has caused the development of a group of nickel-base alloys which are strengthened by precipitation hardening. The composition of some of the most familiar of these alloys is given in Table 1.

Practically all of the precipitation-hardening alloys contain aluminum and titanium. Strengthening is due to the precipitation of a nickel-aluminum-titanium phase, $Ni_3(Al, Ti)$, (γ'), during properly designed heat treatments. The usual heat treatment is a two-step procedure. A first step, called a solution treatment, involves heating to and holding at temperature and then cooling in a manner which retains the elevated-temperature structure. The second step, called an aging treatment, involves heating to and holding at an intermediate temperature which causes the precipitation of a dispersed $Ni_3(Al, Ti)$ phase which is unstable at elevated temperature. Variations in heat treatments are made, depending on the type of stresses the final assembly must withstand. An example of this is given in Figure 9.[18] Unfortunately, the best heat treatment for a particular application is not always the best for optimum welding. The presence of aluminum and titanium, plus the complex heat treatments required for their full utilization, makes the welding of age-hardenable alloys tricky. Highly controlled welding procedures are required in order to obtain reproducible results.

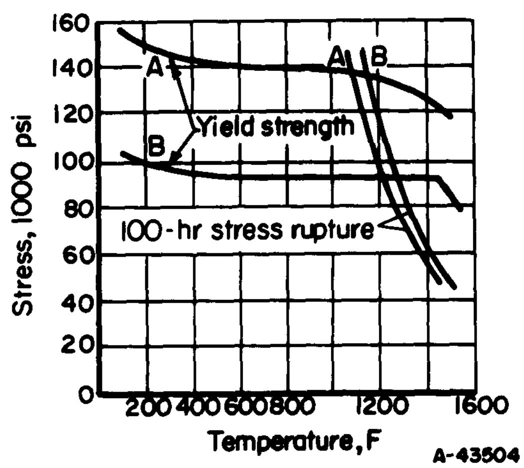


FIGURE 9. EFFECT OF HEAT TREATMENT ON YIELD STRENGTH AND STRESS-RUPTURE PROPERTIES[18]

For best tensile strength (A), solution treat at 1950 F, air cool to room temperature, and age at 1400 F. For best stress-rupture properties (B), solution treat at 2150 F, cool to room temperature, and age 4 hr at 1650 F.

Fusion Welding

The first requisite for successfully joining age-hardenable nickel-base alloys is cleanliness. In this respect, they are like all nickel alloys. All paint, oil, crayon, shop dirt, or other surface contaminants must be removed to avoid the possibility of embrittlement.

The precautions necessary for success after proper cleaning can be generalized as follows:

(1) Avoid welding on parts which are stressed in any way; from cold work, thermal expansion or contraction, or restraint during welding.

(2) Weld only on annealed or solution-treated parts if possible.

(3) Use the minimum heat input conducive to good welds.

(4) Do not preheat.

(5) Clean weld thoroughly between passes and before heat treating, especially if coated electrodes are used.

(6) Charge welded parts into hot furnaces for heat treatment to minimize time in the aging range.

(7) Design and locate welds to minimize restraint, heat input, cleaning problems, etc.

Attention to these precautions is evident in the reported work on joining of such alloys as Inconel X, René 41, M-252, R-235, Waspaloy, the Nimonic alloys, and others. Some of the details are discussed in the following paragraphs.

Inconel X

Inconel X is one of the older age-hardenable nickel-base alloys. Because of this, considerably more published data, especially on resistance welding, are available on its fabrication than on the newer alloys. This broad experience is probably one of the reasons Inconel X was chosen for use in the X-15 rocket plane.

Inconel X can be welded by most conventional processes. However, some processes are used at a sacrifice in joint efficiency. It should always be welded in the annealed or solution-treated condition. It has been recommended that Inconel X not be welded if the hardness is greater than 25 R_C.[19] The ductility of the alloy in the range 1200 to 1500 F depends on hardness. If the ductility is too low in this temperature range, the base metal would probably crack because it could not withstand the strains set up during welding or remaining from forming operations.

Spicer[20] in discussing the importance of stresses when welding Inconel X reports that they can be overcome by applying proper thermal treatments at proper intervals. If a part is simple, it may be necessary to stress relieve only between welding and age hardening. If the part is complex, or made from several subassemblies, the subassemblies should be stress relieved before final welding into the unit. Then the complete

part should be given a stress-relief treatment before age hardening. Spicer gives the thermal treatments used in fabrication of Inconel X.

Stress relief	1650 F for 2 hours minimum
Anneal	1950 F for 15 to 30 minutes
Solution treatment	2100 F for 2 to 4 hours
Direct age	1300 F for 20 hours
Double age	1550 F for 24 hours plus 1300 F for 20 hours

The highest possible heating rate should be used because cracking in the low-ductility range is a function of time at temperature. Wilson and Burchfield[21] show the advantage of rapid heating schematically in Figure 10.

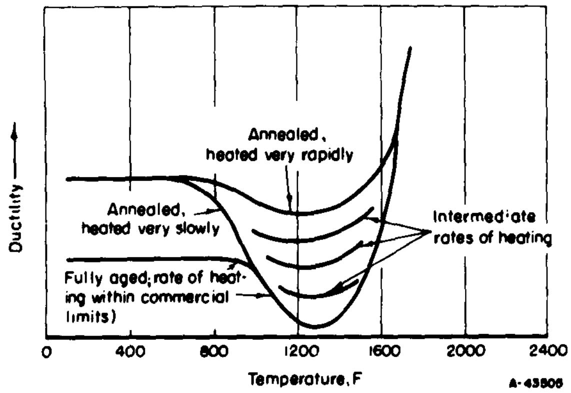


FIGURE 10. INCONEL X – VARIATION OF DUCTILITY WITH TEMPERATURE AND TIME[21]

Schane and Weismantel[22] studied inert-gas-shielded tungsten-arc welding procedures for the fabrication of Inconel X pressure vessels from heavy plate. The importance of attending to details when welding Inconel X was amply demonstrated in their work. Complete removal of surface films after each weld pass by grit (new aluminum oxide) blasting and stainless steel wire brushing was necessary to prevent porosity and stringers. No filler metal was used on the root pass to minimize effects of shrinkage and penetration. On plate less than 1/2 inch thick, angling the torch 20 degrees from the vertical and directing it into one side of the groove gave better grain structure and more uniform root shape. Creep-rupture tests of heat-treated specimens were used in welder qualification to impress the operator with the need to eliminate defects such as lack of fusion due to insufficient cleaning. Figure 11 shows typical design curves developed by Schane and Weismantel for Inconel X when welding procedures were controlled.

During the construction of the research aircraft X-15, North American Aviation acquired considerable experience in the welding of Inconel X. The data in Table 12 are published properties of some of their fusion welds.[23] The advantage of a stress-relief

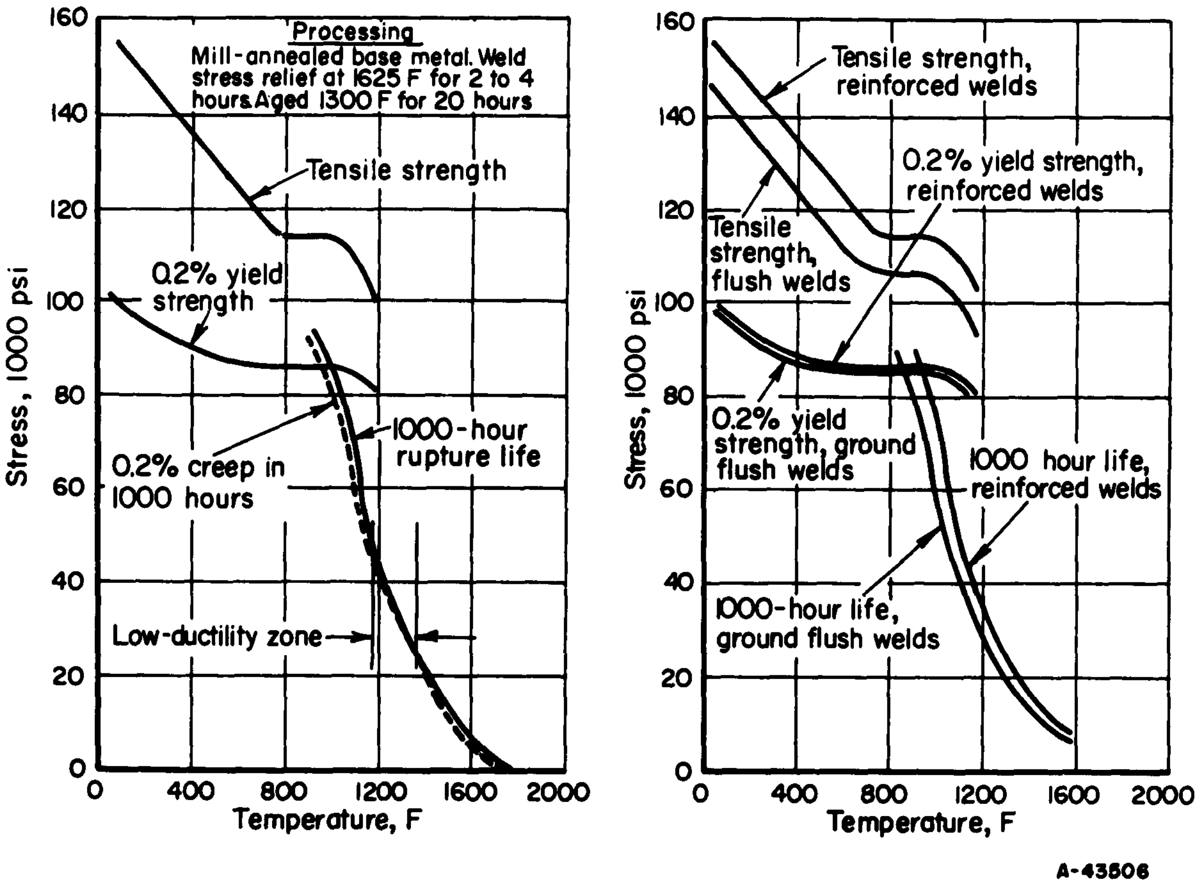


FIGURE 11. INCONEL X—MINIMUM PREDICTED PERFORMANCE VALUES FOR HEAT-TREATED BASE METAL (LEFT) AND WELD METAL (RIGHT)[22]

treatment prior to the aging treatment is quite evident. Also, the data indicate that removal of the weld reinforcement is not advantageous. Results obtained when machined and unmachined butt welds were tested in fatigue showed that removal of the reinforcement is advantageous. The maximum stress versus life-in-fatigue curve for machined welds was above the unmachined curve, but below the parent-metal curve. The machined weld had significantly lower ductility as measured by elongation, however. Thus, the designer must choose the most desirable combination of properties.

TABLE 12. ROOM-TEMPERATURE STRENGTH OF AUTOMATIC TUNGSTEN-ARC INERT-GAS-WELDED 0.093-INCH-THICK INCONEL X USING INCO NO. 69 FILLER WIRE[23]

Heat Treatment After Welding	Joint Condition	Ultimate Tensile Strength of Weld Specimen[a], psi	Ultimate Tensile Strength of Parent Metal, psi
1625 F-4 hr, 1300 F-10 hr	Weld ground flush	154,000	176,000
1625 F-4 hr, 1300 F-10 hr	Reinforcement left on	176,300	176,000
1300 F-10 hr	Weld ground flush	143,000	172,000
1300 F-10 hr	Reinforcement left on	172,000	172,000

(a) Average of five specimens.

Cooper and Pease[24] have published welding conditions, Table 13, for Inconel X sheet with the tungsten-arc process. They used a 2 per cent thoriated tungsten electrode and a grooved copper backup.

TABLE 13. WELDING CONDITIONS FOR INCONEL X WHEN USING ARGON-SHIELDED TUNGSTEN-ARC PROCESS[24]

Material Thickness, inch	Current, amperes	Arc Voltage, volts	Weld Speed, ipm	Argon Gas Flow, cfh
0.032	40-52	9-10	12-17	10
0.050	70-90	9-10	12-17	10
0.063	80-95	9-11	11-15	10
0.094	110-128	10-12	8.5-11	11

McDonnell Aircraft[25] has reported on the effect of short-time elevated-temperature tests on welded Inconel X. The welds were all in 0.043-inch sheet and specimens were heat treated after welding, but before machining. Standard tungsten-arc inert-gas shielded welding procedures were used. Two testing procedures were used: (1) heating to the test temperature and testing after a 5-minute hold, and (2) heating to 1400 F, holding 3 minutes, then cooling to the test temperature for testing. The results, which permit the conclusion that cycling to 1400 F does not hurt the strength, are given in Table 14.

TABLE 14. AVERAGE ELEVATED-TEMPERATURE PROPERTIES OF WELDED AND UNWELDED 0.043-INCH INCONEL X SHEET[25]

Test Temp, F	Type Specimen	Yield Strength, psi	Ultimate Strength, psi	Elongation, per cent
Room	Unwelded	125,000	179,500	23
Room	Welded	128,000	171,500	16
600	Welded	118,000	158,000	23
800	Welded	115,000	151,000	19
1000	Welded	117,000	143,000	14
1200	Welded	110,500	120,000	5
1400	Welded	93,500	97,000	2
1600	Welded	52,500	53,500	7
1800	Welded	14,000	14,000	27
1400/600	Welded	122,000	150,000	19
1400/800	Welded	110,000	147,000	22
1400/1000	Welded	109,500	142,500	22
1400/1200	Welded	112,500	121,000	5
1400/600	Unwelded	112,000	157,000	26
1400/800	Unwelded	113,500	152,000	26
1400/1000	Unwelded	112,000	145,500	26
1400/1200	Unwelded	109,500	117,500	6

In another study[26], McDonnell evaluated the effect of welding technique on the properties of welded 0.375-inch Inconel X plate. Three different multipass welding techniques were used:

(1) The first weld pass was with Hastelloy W filler, the remaining passes with INCO No. 69 filler. Hastelloy W was used to give ductility.

(2) All weld passes were with INCO No. 69, but each pass was hammer peened. Peening was used to reduce grain size and improve weld structure.

(3) All weld passes were with INCO No. 69.

Standard welding procedures, stress relief, and heat treatments were used.

Essentially equal strength joints were obtained in every case. The welds containing Hastelloy W had greater elongation than did welds where it was not used. Hammer peening did break up the coarse columnar structure of the weld and, in doing so, probably lowered the chances of crack propagation in the weld.

Inconel W

Inconel W is very similar to Inconel X. Their compositions vary mainly in the lack of columbium in Inconel W. Welding characteristics are the same for both alloys and the same general precautions are required for successful welding. Inconel W is included here to permit the recording of the unorthodox but successful welding of an age-hardened nickel-base alloy.

General Electric[27] evaluated the feasibility of welding 1-inch-thick age-hardened Inconel W to 1-inch-thick Inconel. The Inconel W plates were fully aged and then welded manually using MIL-4N85 electrodes and automatically tungsten-arc inert-gas-shield welded using MIL-RN87 filler wire. Evaluation of the resultant welds included guided-bend and tensile tests. It was concluded that age-hardened 1-inch-thick Inconel W to Inconel welds can be made in the fully restrained condition.

It would seem that the success of this case of welding in the heat-treated condition can be attributed to the fact that dissimilar metals were being welded. The presence of ductile non-heat-treatable Inconel as one part of the joint permitted enough strain to occur to prevent cracking.

René 41

René 41 is an austenitic nickel-base precipitation-hardening alloy. It was developed by the General Electric Company as a jet-engine alloy with excellent high-temperature strength and oxidation resistance. Recommendations given by Weisenberg and Morris[18] best cover the prcper way to fusion weld René 41.

(1) Material must be properly annealed before welding. This means in the 1975 F mill-annealed condition. Cold-worked parts may crack when welded. In process, anneals should be at 1975 F and followed by a fast quench.

(2) Good fit up is always required. Burrs should be ground from joint edges before welding. On butt joints, the joint must be protected by inert gas. On other joints, inert-gas protection should always be used. Copper backing should be used whenever possible. Joint designs which minimize restraint must be used. (See Figure 12.)

(3) Welding should be controlled for minimum heat input. Automatic welding using Hastelloy W or Hastelloy X filler materials is preferred.

Consistently sound welds can be made only by following recommended practices. René 41 has small tolerance for procedural variations. Careless welding can cause cracking either during welding or after heat treatment.

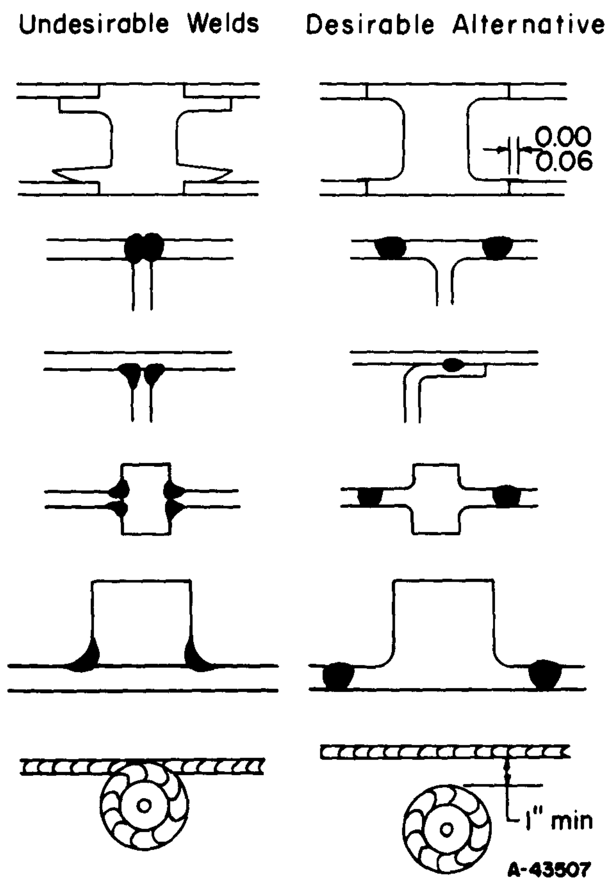


FIGURE 12. JOINT DESIGNS FOR WELDING RENÉ 41[18]

(Also desirable for any alloy which must be welded with minimum restraint.)

Welding of aged René 41 is virtually impossible. Full annealing is required prior to repair welding.

Boeing[17] in the development of fusion welding parameters for René 41 sheet material obtained acceptable manual welds with the conditions given in Table 15. Those obtained for mechanized welding are given in Table 16. All of the usually required joint preparation and cleaning operations were carefully adhered to in producing the welds. It is assumed that sheared wires from the base-metal sheet were used as filler metal.

TABLE 15. CONDITIONS FOR MANUALLY BUTT WELDING RENÉ 41 BY THE TUNGSTEN-ARC INERT-GAS PROCESS[17]

Material Thickness Combination	Wire Diameter, in.	Current		Estimated Torch Speed, ipm
		Volts	Amperes	
0. 040 to 0. 040	0. 040	12	60	2. 15
0. 020 to 0. 020	0. 040	12	30	3. 00

Boeing made lap fusion welds in 0. 040-inch-thick René 41 and chose the settings in Table 17 for successful full-penetration welds. Both mechanized and manual welds were made.

Another reference[28] gives the following "typical" conditions for tungsten-arc inert-gas welding of 0. 010-inch-thick René 41.

Power	300-amp d-c rectifier
Electrode	Pointed, 1/16 inch, 2 per cent thoriated
Gas	Primary argon 15 to 20 cfh; backup helium 5 to 7 cfh
Amperage	Start 45 amperes high frequency, slope to 30 amperes
Backups	Watercooled copper, 1/16-inch-deep groove

The process details call for a 1/16-inch flange at the butting edges. A first pass is then made at 12 ipm to close the flange ends. A second pass at 6 ipm completes the weld. Flanging is a common method of getting filler metal or minimizing burnthrough in thin materials. The effect of the cold work in the René 41 caused by flanging was not discussed. Beemer and Mattek[16], in their study of the inert-gas tungsten-arc welding of thin-gage nickel-base alloys, give the welding conditions for René 41 shown in Tables 6 and 7. The resultant mechanical properties are also given in these tables. This reference should be sought by welders and users of thin-gage René 41.

McDonnell[44] has also reported recently on the fusion welding of René 41. No mention of cracking during or after the welding of aged specimens was made.

A very large portion of the original welding-procedure-development studies on René 41 was done by the General Electric Company, Large Jet Engine Department,

TABLE 16. CONDITIONS FOR MECHANIZED BUTT WELDING RENÉ 41 BY THE TUNGSTEN-ARC INERT-GAS PROCESS WITHOUT FILLER WIRE[17]

Gage Combination, inch	Welding Current		Torch Speed, ipm	Torch Gas		Backup Gas	
	Amperes	Volts		Type	Cfh	Type	Cfh
0.010 to 0.010	15	8.5	21	Argon	30	Argon	7.5
0.020 to 0.020	20	7.5	10	Argon	20	Argon	7.0
0.040 to 0.040	16	15.0	11	Argon	90	Argon	5.0

TABLE 17. SETTINGS FOR TUNGSTEN-ARC INERT-GAS-WELDED LAP JOINTS[17]

Procedure	Current		Torch Speed, ipm	Torch Gas		Backup Gas		Wire Feed, ipm
	Amperes	Volts		Type	Cfh	Type	Cfh	
Manual	39	8.5	6.0	Argon	11	Argon	4	2.6
Mechanized	74	7.5	8.5	Argon	35	Argon	10	--

Cincinnati, Ohio. Several of their reports published in the last 5 years on "Welding, Brazing, and Fabrication of René 41"(29) have recently been compiled and released under Air Force Contract AF 33(657)-8017. The titles of the several items in this compilation that deal with fusion welding and a brief extract of the results are given in the following paragraphs. None of the specific data are reproduced. This is because, in most cases, the work was on a laboratory scale with no specific production problem in mind. Also, most of the base metal used was from experimental heats of René 41 at a time when the composition and processing details were not well established. This report should be very useful to those who (1) are just beginning to use René 41, (2) anticipate new applications, (3) wish to alter accepted procedures, or (4) desire to change the composition for some reason.

1. Weldability of René 41 Alloy Sheet

   Covers manual and machine tungsten-arc inert-gas welding and spot welding. No difference in mechanical properties was found between manual welds using filler and machine welds without filler. Mechanical properties were similar for both welded and unwelded base metal. Dross formation during welding caused some concern. Spot welds were comparable to Inconel for tension-shear strength.

2. Investigation of Cracks on Weld Panels

   Study of the effects of various solution treatments on René 41 weld-crack susceptibility. Welds and base metal cracked on aging at 1400 F after being given a 2150 F, 0.5 hour, and water quench treatment before welding. Samples treated given treatments of 1950 F, air cool; 1950 F, water quench; and 2050 F, water quench did not crack.

3. Welding of High-Boron René 41 Sheet

   Boron increases in experimental heats for other metallurgical reasons did not change weldability. Boron content considered high at 0.0087 weight per cent.

4. Strength Data on René 41 Welded With Hastelloy W

   No problems encountered when using tungsten-arc inert-gas welding. No increase in strength. Tensile strength drops rapidly above 1200 F. Hastelloy W minimizes cracking.

5. Mechanical Properties of René 41 Sheet Welded to Itself and to L-605 Using Various Filler Metals

   Tensile and stress-rupture tests used to determine properties and the effect of various heat treatments.

6. Mechanical Properties of Welded René 41 Using Various Fillers

   Bar stock, 3/8-inch in diameter, tungsten-arc inert-gas and flash welded. Sheet stock, 0.080 to 0.090 inch thick spot welded. Sheet

3/16 inch thick butt and fillet welded. Tensile, hardness, stress rupture, and impact properties tabulated. Different postweld heat-treatment studied; crack susceptibility evaluated.

7. Fatigue Properties of René 41 Welded Sheet

   Butt welds and T-joints made in 0.066-inch sheet. Good welds do not significantly affect the fatigue life of the parent material. Data are plotted.

8. Weld Design for René 41

   This report is essentially for public consumption. The material is recognizable in several publications.

9. Effect of Welding on Mechanical Properties

   Actually a report on the welding of René 41 castings to René 41 sheet. Tungsten-arc inert-gas welding successful. Joints all fail in the cast metal. Stress rupture properties comparable to those of sheet. Either a-c or d-c current can be used, but film or dross on weld pool when using d-c current is troublesome.

10. Mechanical Properties of Sheet After Various Welding Procedures

    Properties of weldments in René 41, Udimet 500, and two other high-temperature alloys determined. Only data on René 41 are given in this report.

Waspaloy

The precipitation-hardening nickel-base alloy Waspaloy was developed as a forging alloy. It is available in other forms such as sheet and plate. Waspaloy contains both boron and zirconium to enhance its elevated-temperature properties.

The requirements for successful fusion welding of Waspaloy are essentially the same as those for other nickel-base hardenable alloys. The boron and zirconium concentrations apparently are not high enough to cause trouble. It should always be welded in the solution-treated condition. Waspaloy is solution treated by soaking at 1975 F for 4 hours followed by air cooling.

When in the proper condition, Waspaloy presents no new problems. When welding sheet, holddown and backup blocks should be used. Metallic-arc welding should be used only on heavier sections.(30) Precautions with respect to cleaning, joint preparation, welding technique, etc., are the same as for other nickel-base precipitation-hardening alloys.

Hastelloy R-235

Hastelloy R-235 is another nickel-base alloy containing aluminum and titanium to give it precipitation-hardening properties. Its resistance to overaging in service and

good impact strength have made it attractive for use at elevated temperatures. Also, the heat treatments required to obtain maximum properties are simpler than those for most alloys of this type. Hastelloy R-235 is produced by vacuum melting.

Marquardt[31] conducted a rather extensive study to establish welding conditions and procedures for manually butt welding Hastelloy R-235 sheet. They evaluated filler metal (Hastelloy R-235 and Hastelloy W), backup-bar material (steel and copper), and backup-gas flow rate. The effect of roll leveling on weld tensile properties was determined to see whether or not it was feasible to utilize this alloy's high work-hardening characteristics. In preparation of specimens for this study, Marquardt found that the normal cleaning procedures for this type of alloy were satisfactory. Weld specimens were degreased in an alkaline solution and then hand ground and wire brushed to remove oxides. Bend and tensile test specimens were machined from welded panels. The room-temperature properties of the welds are given in Table 18. The elevated-temperature properties of roll-leveled welds are shown in Table 19.

The data in Table 18 indicate that greater weld efficiency can be obtained with Hastelloy R-235 filler metal, but welds made with Hastelloy W are more ductile. There was no advantage in using copper backup bars. Roll leveling of the weld bead was beneficial. Hammer leveling caused surface cracks. Gas-flow studies, not shown in Table 18, indicated that argon gas shield can be used. Backup-gas-flow rates of 2 to 4 cfh gave clean welds.

M-252 Alloy

M-252 is a vacuum-melted, precipitation-hardening, nickel-base alloy suitable for service at temperatures up to about 1400 F. Like Waspaloy, M-252 contains small additions of boron and zirconium for high-temperature strength. M-252 has the same welding characteristics as most other nickel-base alloys. Proper attention to cleaning, welding technique, base-metal condition, etc., permits successful welding. Weldments having 100 per cent joint efficiencies have been made.

In a preliminary welding study[32], the following average data were recorded for 0.060-inch sheet stock welded in the mill-annealed condition.

Specimen	Yield Strength, psi	Ultimate Strength, psi	Elongation, per cent	Bend Radius
Base metal	82,900	134,800	--	0.5T
Weldment[a]	63,400	125,000	92	2.0T

(a) All specimens broke in the weld.

The objective of another investigation[33] was to determine the properties of welds made in M-252 after two different solution treatments. The work was done on 0.040-inch-thick sheet. M-252 was butt welded in the 1950 F and in the 2125 F solution-treated condition. After welding, the specimens were aged at 1400 F for 16 hours, the weld beads were removed, and then the specimens were tension tested. Some specimens were overaged at 1400 F for 400 hours. The results are summarized in Table 20.

TABLE 18. PROPERTIES OF MANUAL METAL-ARC INERT-GAS-SHIELDED WELDS IN HASTELLOY R-235 SHEET[a], WELD GROUND FLUSH[31]

Test Condition	Yield Strength, 0.2 Per Cent Offset, psi	Ultimate Strength, psi	Elongation in 1 Inch, per cent	Joint Efficiency, per cent	Minimum Bend Radius
Base metal	97,000	144,500	46	--	0.5T
R-235 filler, steel backup	83,600	129,700	21	89.6	2.4T
Hastelloy W filler, steel backup	68,600	117,000	16	81.0	1.5T
R-235 filler, copper backup	83,200	128,500	20	89.0	2.4T
Hastelloy W filler, copper backup	76,800	114,200	14	79.0	1.5T
R-235 filler, steel backup, roll leveled	91,000	138,300	22	95.7	3.0T
No filler steel backup, roll leveled	90,300	128,200	17	89.0	2.7T

(a) Actual thickness not given.

TABLE 19. PROPERTIES OF ROLL-LEVELED AND FLUSH-GROUND FUSION WELDS IN 0.063 INCH HASTELLOY R-235 SHEET[31]

Test Temperature, F	Yield Strength, psi	Ultimate Strength, psi	Elongation in 2 Inches, per cent	Modulus of Elasticity, 10^6 psi
70	74,700	125,500	45	27.0
1800	27,000	34,300	17	--[a]
2000	8,300	11,600	27	--[a]
2200	3,800	6,600	20	--[a]

(a) Broke in base metal. Strain rate 0.001 in./in./sec.; hold time 15 minutes.

TABLE 20. STRENGTH OF BUTT WELDS IN M-252 SHEET ALLOY[33]

	As Aged			After 400 Hours at 1400 F		
Solution Temperature, F	Yield Strength, psi	Ultimate Strength, psi	Elongation, per cent	Yield Strength, psi	Ultimate Strength, psi	Elongation, per cent
1950	130,000	150,000	1-6	105,000	150,000	0-5
2125	100,000	100,000	5-13	100,000	130,000	2-5

It is interesting to note that the original data for Table 20 indicates failure in the heat-affected zone on 62 per cent of the welds made after a 1950 F solution treatment. Only 28 per cent of the specimens solution treated at 2150 F failed in the heat-affected zone. Also, weld cracking contributed to failures in 22 per cent of the specimens solution treated at 1950 F and none of those treated at 2150 F.

Inconel 718

Inconel 718 is age hardenable mainly because of the addition of columbium rather than titanium and aluminum as in the case of other nickel-base age-hardenable alloys. Studies have shown that Inconel 718 is hardened principally by Ni_3(Al-Ti-Cb), i.e., a columbium-bearing gamma prime (γ'). It is unique in this respect. The composition of this alloy is given in Table 1. Because of its particular age-hardening characteristics, Inconel 718 can be welded in the age-hardened condition and in more highly restrained conditions than the other alloys. In sections up to at least 0.5 inch it is not necessary to use stress-relief treatments after welding. Some heat-affected-zone softening is encountered when welding the hardened alloy. The sluggish precipitation of submicroscopic age-hardening columbium-bearing compounds permits annealing and welding without serious hardening during heating and cooling.

The usual joint preparation and cleaning requirements are applicable to Inconel 718. Fusion welding usually is done by the inert-gas tungsten-arc process. Good gas coverage both on face and root of the joint is required. Several filler metals have been evaluated for Inconel 718. Some of them are: Inconel 718, Inconel X, René 41, Hastelloy W, and Hastelloy R-235. All produce satisfactory welds. When the joints are restrained, René 41 is the preferred filler metal because of its higher melting temperature. The Huntington Alloy Products Division, The International Nickel Company, published this information on welding Inconel 718.[34,35] They give the data shown in Figure 13 on weld properties.

General Electric has also investigated the weldability of Inconel 718 using a circular-patch weld-restraint test.[36] The results indicated that the alloy could be welded and heat treated under restraint without cracking. The material was 0.063 inch thick and Hastelloy Alloy W was the filler metal used. Tensile and rupture properties were determined. The joint efficiencies obtained for both tensile and 100-hour rupture life were very good, around 92 per cent for tension-tested and 88 per cent for rupture-tested welds. The welding procedures were not given. It is expected that carefully controlled procedures approximating those for René 41 were used. The study also included flash welding of 0.625-inch-diameter hot-rolled bar stock.

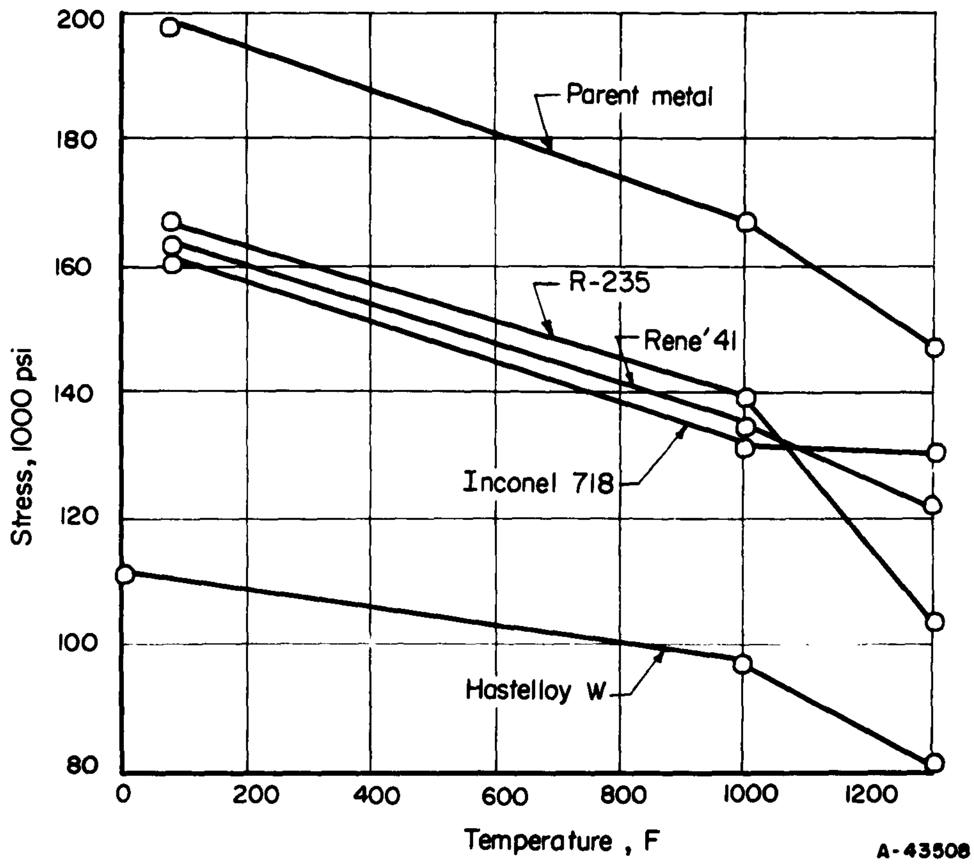


FIGURE 13. TENSILE STRENGTH OF 0.125 INCH INCONEL 718 SHEET WELDED BY THE INERT-GAS TUNGSTEN-ARC PROCESS WITH VARIOUS FILLER METALS

In another investigation covered by the same General Electric report, welding of thick Inconel 718 sheet by a multipass welding technique and the manual inert-gas tungsten-arc process is described. Satisfactory weld joints were made in material up to 0.5 inch thick. Hastelloy R-235 filler wire gave the best tensile and rupture properties (Inconel 69 filler wire also produced strong joints). It was found that argon gas in the torch and backup was not satisfactory for thicknesses over 0.125 inch. Helium gas was preferred for the thicker material. The helium permitted better penetration and gave less porosity. Double U-joints were preferred to aid penetration.

The weldability of Inconel 718 has made it a very attractive alloy for use where age-hardenable nickel-base alloys are desirable.

Nimonic Alloys

The Nimonic alloys have been developed by the British in response to the demand for better gas-turbine alloys. Nimonic 80 is said to be the original precipitation hardening nickel-base alloy. Parallel research in the United States produced Inconel X. The two alloys are basically the same. The compositions of several Nimonic alloys are given in Table 1.

In general, the Nimonic precipitation-hardening alloys require the same procedures and precautions that must be used when fusion welding other alloys of the same type.

Hinde and Thorneycroft[37,38] have thoroughly discussed the metallurgy of welding the Nimonic Alloys. Nimonics 80A and 90 exhibit relatively poor high-temperature properties when welded. Stress-rupture data at 1380 F shown in Figure 14 illustrate this effect and show that solution treatment and aging after welding restores desirable properties. These authors present the conditions given in Table 21 for manual welding of Nimonic alloys.

TABLE 21. ARGON-SHIELDED TUNGSTEN-ARC WELDING CONDITIONS FOR NIMONIC ALLOYS[37]

Material Thickness, inch	Tungsten-Electrode Diameter, inch	Filler-Wire Diameter, inch	Current, amperes	Weld Speed, ipm	Rate of Argon Flow, cfh
0.036	1/16	1/16	75	9	15
0.064	3/32	3/32	100	9	15
0.125	1/8	3/32 or 1/8	150	6	19

Nimonic 100 and 105 are alloys developed for very-high-temperature service. They both contain molybdenum and more aluminum than Nimonics 80A or 90. They are hardened by the same mechanism, but require more complex heat treatments. Fusion welding impairs the creep properties, necessitating corrective postweld heat treatments. These specific treatments are not available.

Experience with Nimonic 100 emphasized the need for rapid heating through certain temperature ranges during postweld heat treatments. This is shown in Figure 15. The temperature range between 1475 and 1750 F is most critical. The high heating rates required are difficult to obtain in thicknesses over 0.10 inch, necessitating modification of heat-treatment schedules.

Differing with investigators in America who prefer inert-gas fusion welding of nickel-base alloys, English and Russian researchers have studied other methods of welding the Nimonic alloys. Gas-shielded metallic-arc welds of 0.060-inch-thick Nimonic 90 using carbon dioxide gas for the shield have shown good mechanical properties.[39] The bead contour, however, is rough. Green discoloration and scum on the weld pool cause some concern. A Russian study[40] claims successful welding of Nimonic type alloys by arcless molten-slag welding. A laminated electrode and a nonoxidizing fluoride-base flux were used. The authors also report success when welding plates (10 to 20 mm or 0.4 to 0.8 inch) by the submerged-arc process.

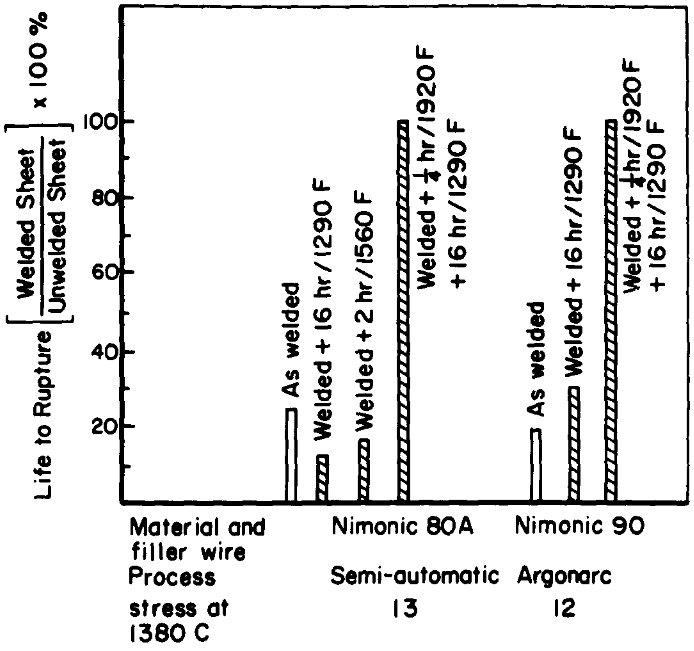


FIGURE 14. EFFECT OF WELDING AND POSTWELD HEAT TREATMENT ON THE STRESS-RUPTURE PROPERTIES OF NIMONIC 80A AND 90 SHEET[38]

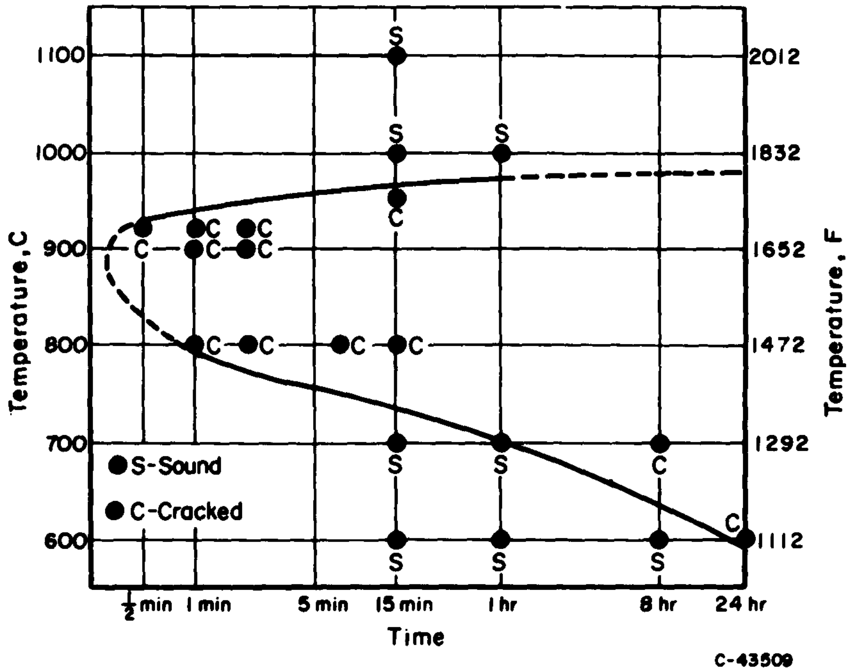


FIGURE 15. INFLUENCE OF TIME AND TEMPERATURE UPON CRACKING IN NIMONIC 100 SHEET HEAT-TREATED AFTER WELDING[38]

Resistance Welding

The standard methods of resistance welding are all useful for the welding of nickel-base precipitation-hardening alloys. The low thermal conductivity and high resistivity of these alloys as compared with steel must be considered when devising welding cycles. Their relatively complex heat treatments and their high strength at elevated temperatures also influence the welding parameters. Cleanliness, as always, cannot be over emphasized.

Data on the resistance welding of precipitation-hardening nickel-base alloys are not plentiful. In general, these alloys can be welded utilizing approximately the same welding parameters as are used for the non-heat-treatable nickel-base alloys. Usually, more pressure and less current is required. This is because of the greater strength and higher resistance of these alloys. Insufficient pressure usually leads to cracking. Too high current may lead to expulsion of molten metal. Cracking may be reduced by using machines having low inertia heads and slope control on the weld cycle.

Inconel X

The optimum spot- and seam-welding conditions for several different thicknesses of Inconel X were determined by Nippes and Fishman.[41] Their criteria for good welds were:

(1) No porosity or cracking in the fusion zone

(2) Less than 5 per cent indentation or 10 per cent sheet separation

(3) Fusion-zone penetration, 30 to 80 per cent to total thickness

(4) Seam-weld fusion-zone overlap 10 to 25 per cent

(5) A wide and reproducible current range.

The results of these studies are given in Tables 22 and 23.

TABLE 22. RECOMMENDED SPOT-WELDING CONDITIONS FOR INCONEL X[41]

Sheet Thickness, inch	Electrode Size, inches: Diameter	Electrode Size, inches: Radius	Weld Time, cycles	Weld Force[a] pounds	Weld Current,[a] amperes	Fusion-Zone Diameter,[a] inch	Penetration, per cent
0.010	5/32	6	2	300	7,300	0.11	45
0.015	5/32	6	4	400	7,400	0.11	45
0.021	3/16	6	6	750	7,500	0.14	35
0.031	7/32	6	8	1750	9,900	0.17	35
0.062	5/16	10	14	4400	16,350	0.29	45

(a) Values are not absolute, but are within a range that is satisfactory for good welds.

TABLE 23. RECOMMENDED SEAM-WELDING CONDITIONS FOR INCONEL X[41]

Sheet Thickness, inch	Wheel Geometry	Speed, ipm	Weld Force[a], pounds	Weld Current[a], amperes	Time, cycles On	Time, cycles Off	Spacing[a], spots/inch	Penetration[b] per cent	Fusion-Zone Width[a] inch
0.010	Mallory No. 3, 1/8 inch wide, 3-inch radius, 9-inch wheel diameter	45	400	3,600	1	3	20	(30-45)	0.11
0.015	Ditto	36	700	3,900	2	4	17	(30-45)	0.12
0.021	Mallory No. 3, 5/32 inch wide, 3-inch radius, 9-inch wheel diameter	30	1400	8,000	3	6	14	(30-45)	0.14
0.031	Mallory No. 100, 3/16 inch wide, 3-inch radius, 9-inch wheel diameter	30	2300	8,500	4	8	10	(30-50)	0.17
0.062[c]	Mallory No. 100, 3/16 inch wide, 3-inch radius, 8-inch wheel diameter	12.5	4000 min	10,300	8	16	12	(30-65)	(0.18)

(a) Values are not absolute, but are within a range which is satisfactory for good welds.
(b) Values in parentheses are ranges.
(c) Not optimum conditions, but satisfactory when sufficient force is not available.

TABLE 24. RECOMMENDED SCHEDULES FOR SPOT WELDING INCONEL X[42]

Material Thickness, inch	Electrode Force, pounds		Time Settings, cycles (60 cps)				Secondary Current, amperes		Minimum Weld Spacing, inches
	Weld	Forge	Weld	Quench	Temper	Forge[a]	Weld	Temper	
				Three-Phase Dry-Disk Rectifier					
0.032	1700	2800	13	0	13	4	6,550	4,400	0.75
0.032	850	1850	22	0	32	5	5,500	4,100	0.75
0.062	2600	4500	35	2	46	8	8,300	5,650	1.25
0.062	1450	2900	44	2	67	9	7,100	5,350	1.25
0.093	3500	6200	55	7	73	14	10,000	7,000	1.6
0.093	2200	3450	65	7	100	14	8,750	6,700	1.6
0.125	4300	7700	73	13	99	18	11,750	8,350	2.1
0.125	3000	5000	78	13	132	19	10,350	8,000	2.1
0.143	4650	8400	83	17	112	21	12,700	9,050	2.4
0.143	3500	5650	101	17	150	20	11,200	8,650	2.4
0.156	4950	8800	89	21	121	24	13,600	9,700	2.7
0.156	3950	6220	113	21	165	23	12,000	9,300	2.7
0.188	5600	9500	100	30	145	28	14,700	10,450	3.0
0.188	4650	7150	133	30	187	26	13,050	10,100	3.0
				Single-Phase Alternating Current					
0.093	3300	6600	54	5	73	14	9,800	7,800	1.6
0.093	2200	4700	66	5	92	13	9,200	7,300	1.6
0.125	4100	7550	70	13	97	18	10,900	8,500	2.1
0.125	3050	5600	90	12	130	18	9,700	7,500	2.1
0.143	4600	8000	79	17	110	20	10,700	8,300	2.4
0.143	3500	6100	102	16	152	20	9,300	7,200	2.4

(a) On single-phase a-c schedules, part of weld time was 5-cycle upslope time. The initial current was 30 per cent of the maximum welding current.

Electrodes: 0.032-0.062; RWMA Class III, 6-inch-radius dome; diameter 0.88 inch
0.093-0.125; RWMA Class II, 8-inch-radius dome; diameter 0.88 inch
0.143-0.188; RWMA Class II, 8-inch-radius dome; diameter 1.5 inches.

Another study of Inconel X spot welding (Harris, Bellware, and Riley[42] covered the thickness range 0. 032 to 0. 188 inch. The results of this study are given in Table 24.

Both of the investigating teams referenced above emphasize the importance of cleanliness and uniformity of surface condition. Both also recommend the cleaning procedure given in Figure 16. Other comments concerned the presence of coring in spot welds. Neither team found any detrimental effect of coring. Careful measurement of contact resistance has indicated that good welds are obtained consistently only when the contact resistance is below about 80 microhms.

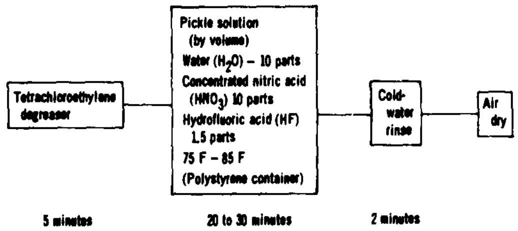


FIGURE 16. CHEMICAL CLEANING OF INCONEL X[42]

North American Aviation[23] has published the spot- and seam-weld strength data presented in Tables 25 and 26. The strengths and weld diameters compare well with those of Harris.

TABLE 25. SPOT-WELD STRENGTHS FOR INCONEL X TO INCONEL X[23]

Sheet Thickness, inch	Nugget Diameter, inch	Penetration, per cent	Shear Strength, psi: As Welded	Shear Strength, psi: Aged 10 Hours at 1300 F	Test Temperature, F
0. 050	0. 22	50	--	4,230	-300
0. 050	0. 22	50	--	3,680	RT
0. 050	0. 22	50	--	3,460	400
0. 050	0. 22	50	--	3,200	800
0. 050	0. 22	50	--	2,815	1,200
0. 050	0. 22	45	2,900	4,300	RT
0. 060	0. 28	50	3,500	4,500	RT
0. 092	0. 34	40	5,000	7,200	RT
0. 130	0. 36	35	8,970	10,600	RT

Inconel W

Optimum spot- and seam-welding conditions for Inconel W were developed by Nippes, Savage, et al.[43] Some of their results are given in Tables 27 and 28. In general, these conditions are very similar to those for Inconel X. Cleaning and contact resistance requirements are the same. Wider current ranges are permissible. Electrode alignment is an important consideration in thin gages.

TABLE 26. SEAM-WELD STRENGTHS[a, b] FOR INCONEL X TO INCONEL X[23]

Specimens stress relieved and precipitation hardened after welding.
Stress relief – 1625 F, 4 hours.
Hardening – 1300 F, 10 hours, air cool.

Specimen Type	Sheet Thickness, in.	-300 F Lb/In.	-300 F % PM[c]	-300 F % RT[d]	80 F Lb/In.	80 F % PM[c]	600 F Lb/In.	600 F % PM[c]	600 F % RT[d]	1200 F Lb/In.	1200 F % PM[c]	1200 F % RT[d]
Lap-shear	0.043 - 0.043	7,400	93	121	6,100	92	5,300	84	87	4,300	91	70
	0.093 - 0.093	13,500	68	119	11,400	67	9,600	59	84	6,600	54	58
	0.125 - 0.125				14,200	59				8,600	52	61
	0.043 - 0.050				6,200	94						
	0.043 - 0.093	6,800	85	113	6,000	91	5,700	91	95	4,600	97	76
	0.050 - 0.093				8,200							
	0.043 - 0.043				6,400	97						
	0.093 - 0.093				16,899	100						
	0.125 - 0.125				22,700	95						
U-tension												
	0.043 - 0.043				2,900	47						
	0.093 - 0.093				6,000	52						
	0.043 - 0.093				3,600	60						
	0.050 - 0.093				3,000	36						
Parent metal	0.043	7,800		118	6,600		6,100		92	4,700		71
	0.093	19,500		116	16,900		16,000		94	12,200		72
	0.125	26,500		113	23,200					16,500		71

(a) Strength is in pounds per lineal inch of weld.
(b) Each value is average of three tests.
(c) Per cent of parent-metal strength.
(d) Per cent of room-temperature strength.

TABLE 27. RECOMMENDED SPOT-WELDING CONDITIONS FOR INCONEL W[23]

Gage, inch	Electrode Size, inches		Weld Time[a], cycles	Weld Force[a], pounds	Weld Current[a], amperes	Fusion-Zone Diameter[a], inch	Penetration, per cent
	Diameter	Radius					
0.010	5/32	6	2	300	6,400	0.11	60
0.015	5/32	6	4	450	7,000	0.10	40
0.021	3/16	6	6	850	9,000	0.13	35
0.031	7/32	6	8	1750	9,200	0.17	40
0.062	5/16	10	14	4400	16,800	0.31	55

(a) Values are not absolute, but represent conditions within specified ranges which are satisfactory for good welds.

TABLE 28. RECOMMENDED SEAM-WELDING CONDITIONS FOR INCONEL W[43]

Gage, inch	Wheel Material and Geometry	Speed[a], ipm	Force[a], pounds	Current[a], amperes	Time[a], cycles On	Time[a], cycles Off	Spacing[a], spots/inch	Penetration[b], per cent	Fusion-Zone Width[a], inch
0.010	RWMA Class II, 1/8 inch wide, 3-inch radius, 9-inch wheel diameter	45	400	4,900	1	3	20	(30-60)	0.11
0.015	Ditto	36	700	6,400	2	4	17	(30-60)	0.12
0.021	RWMA Class II, 5/32 inch wide, 3-inch radius, 9-inch wheel diameter	30	1400	7,600	3	6	14	(30-60)	0.14
0.031	RWMA Class III, 3/16 inch wide, 3-inch radius, 9-inch wheel diameter	30	2300	9,700	4	8	10	(30-60)	0.17
0.062[c]	RWMA Class III, 1/4 inch wide, 6-inch radius, 8-inch wheel diameter	12.5	4000 min	14,400	8	16	12	(30-60)	0.24

(a) Values represent conditions within specified ranges.
(b) Values in parentheses are specified ranges which give satisfactory welds.
(c) Not optimum conditions, but satisfactory when sufficient force is not available.

Rene 41

Resistance-welding information for René 41 is not plentiful. Welding conditions and weldment properties have been reported by Boeing, General Electric, and others.

Boeing[17] has established recommended welding conditions for spot welding several different sheet thicknesses. These conditions are given in Table 10. René 41 is very susceptible to cracking. Other applicable comments are included under Hastelloy X in this report. They are equally applicable to René 41. Close control of cleaning and all other process variables must be maintained.

In early work on the evaluation of its weldability, General Electric[29] spot welded René 41 using the following schedule:

Machine	50 KVA, single phase, press type
Squeeze Time, cycles	120
Heat Time, cycles	30
Upslope Time, cycles	15
Off Time, cycles	15
Number of Pulses	3
Electrode Force, pounds	2140
Electrodes	RWMA Class III, 4-inch spherical radius face

The results are summarized in Table 29. The General Electric results indicate that René 41 can be spot welded in either the annealed or hardened condition with little effect on the weld strength. The tension-to-shear ratio, usually a measure of spot-weld ductility, was comparable to that for Type 321 stainless steel for this early work. Other results reported on later studies indicate the ductility ratio at a much lower value. But the welding schedule, particularly the electrode force, was quite different, indicating the need for further study.

Much more recent data on the spot welding of René 41 are found in the work of Beemer and Mattek.[16] Their data are given in Table 11. The resistance welding of René 41 requires higher electrode pressures and more accuracy and flexibility of control than do stainless steels. This is also true for all other age-hardenable nickel-base alloys.

McDonnell Aircraft[44] in a resistance-welding study on 0.025-inch-thick René 41 encountered no problems except with expulsion between sheets. Shear failure loads for single spot welds were as follows:

Welded in the solution-treated condition	1100 lb
Welded in the solution-treated and aged condition	1045 lb
Welded in the solution-treated condition, then aged	1175 lb

The welding conditions were predetermined with a pressure of 1600 pounds on a 4-inch-tip-radius electrode, using a minimum contact diameter of 0.25 inch.

TABLE 29. PROPERTIES OF SPOT WELDS IN RENÉ 41[29]

Number of Tests	Material Condition	Strength, lb		Weld Diam, inch	
		Range	Average	Range	Average
	Tensile-Shear Tests on 0.062-Inch Sheet				
9	Mill annealed	3140-3400	3300	0.235-0.245	0.239
10	Solution treated and aged[a]	3380-3700	3500	0.235-0.250	0.247
	Cross-Tension Tests on 0.062-Inch Sheet				
10	Mill annealed	2280-2600	2400	0.240-0.250	0.246
10	Solution treated and aged[a]	2200-2520	2400	0.240-0.255	0.249

(a) 2150 F solution, 1/2 hour, air cooled; 1650 F, age 4 hours, air cooled.

The room-temperature mechanical properties of flash welds made by General Electric[29] in 0.625-inch-round bar stock are given in Table 30. These laboratory flash weld results indicate the possibility of producing welds which are 90 per cent efficient based on yield strength. However, flash welds made outside the laboratory from the same material had much lower strengths.

A good portion of the results of spot-welding and flash-welding studies that have been reported for René 41 are relatively old. Newer work has no doubt permitted the development of more reliable information. Not much of this information has been published, however.

Waspaloy, Hastelloy R-235, and M-252 Alloy

Very few data on actual resistance welding of these alloys have been reported. Those studies that have been reported indicate nothing different from other age-hardenable nickel-base alloys so far as resistance welding is concerned. All report that these alloys

TABLE 30. MECHANICAL PROPERTIES OF FLASH WELDS IN RENÉ 41 ROUND BAR(29)

Heat Treatment	Diam, inch	Ultimate Load, psi	Yield Strength (0.2% Offset), psi	0.2% Yield Strength, psi	Reduction in Area, per cent	Elongation, per cent	Fracture Locations(a)
				Weld Properties			
B50T44C	0.2520	186,400	123,200	139,700	8.6	9.5	PM
Ditto	0.2520	184,400	119,800	137,100	12.4	10.0	PM
"	0.2515	185,300	120,900	138,100	12.0	9.0	Weld
"	0.2500	186,600	122,200	137,700	10.1	11.0	PM
"	0.2505	173,200	123,500	137,900	10.5	7.0	PM
				Approximate Base-Metal Properties			
"	0.2470	198,000	131,000	150,000	20.4	16.3	---

(a) PM = parent metal.

are not easy to weld. The importance of machine control variables is repeatedly emphasized. They are extremely critical. To make acceptable spot or seam welds control variables must be exact. This was discussed previously.

Boeing[45], in developing suitable techniques for spot welding M-252 alloy, decided that the best sequence for producing spot-welded assemblies was: solution heat treat, age, and then weld. But very limited results indicated that, if aging followed welding, the fatigue properties were better.

Nimonic Alloys

Waller and Knowlson[12] have recently reported the spot welding of Nimonic alloys. Also, Knowlson[46] has reported on the factors affecting the formation of cracks in spot welds in the Nimonic alloys. The alloys covered by these investigators are Nimonic 75, Nimonic 80A, and Nimonic 90. Because of the similarity between Nimonic alloys and domestic nickel-base alloys, the information given should be of great interest. The conditions for spot welding Nimonic alloys are given in Table 31. Tables 32 and 33 summarize the strength of spot welds with the base metal in several different conditions. It was shown that cracking could be reduced by increasing electrode pressure and weld time. Cracking was related to weld nugget size. Nuggets that are large in relation to the electrode tip size are less likely to crack. This is in line with the longer-weld-time benefits. Higher currents or longer weld times give larger nuggets.

TABLE 31. RECOMMENDED CONDITIONS FOR SPOT WELDING NIMONIC ALLOYS[12]

Material	Thickness, s. w. g.	Force, lb	Time, cycles	Current, 1000 amp	Current Value for Splashing, 1000 amp	Electrode[a] Tip Diam, in.
Nimonic 75, annealed	16	2500	20	8.8	9.4	0.25
	18	1500	15	6.2	6.7	0.25
	22	1000	10	6.0	6.3	0.1875
Nimonic 80A, solution treated	16	2500	20	7.85	8.6	0.25
	18	2000	25	7.7	8.2	0.25
	22	750	10	5.5	5.9	0.1875
Nimonic 90, solution treated	16	2500	45	6.3	7.0	0.25
	18	2250	20	7.4	7.8	0.25
	22	750	10	5.8	6.2	0.1875
Nimonic 90, solution treated and age-hardened before welding	16	3000	45	5.4	--	0.25

(a) Electrodes 0.8 per cent beryllium, 2.2 per cent cobalt, balance copper; truncated cone 120-deg included angle.

TABLE 32. RESULTS OF STRENGTH TESTS ON SPOT WELDS IN NIMONIC ALLOYS

Material	Thickness, s.w.g.	Shear Strength, tons	Coefficient of Variation, %	+ Tension Strength, tons	Coefficient of Variation, %	Ductility Ratio, %	Theoretical Tension Strength, tons	Tension Ratio, %
Nimonic 75, annealed	16	1.48	1.1	1.08	3.9	73	1.20	90
	18	0.94	2.9	0.75	2.1	79	0.90	83
	22	0.52	6.2	0.33	5.6	63	0.41	80
Nimonic 80A, solution treated	16	1.79	3.1	1.57	3.7	88	1.36	115
	18	1.09	2.1	0.65	3.1	60	0.94	69
	22	0.47	1.6	0.41	2.5	88	0.39	105
Nimonic 90, solution treated	16	1.50	1.2	1.14	3.3	76	1.42	80
	18	1.27	4.5	0.81	4.3	64	1.06	76
	22	0.52	2.7	0.39	2.5	75	0.44	89
Nimonic 90, solution treated and age hardened before welding	16	1.68	4.7	1.24	3.5	73	--	--

TABLE 33. RESULTS OF STRENGTH TESTS OF POSTWELD FURNACE-AGED SPOT WELDS IN NIMONIC ALLOYS

Material and Post-Weld Heat Treatment	Thickness, s.w.g.	Shear Strength, tons	Coefficient of Variation, %	Average Nugget, Diam., in.	U-Tension Strength, tons	Coefficient of Variation, %	Average Nugget Diam., in.	Ductility Ratio, %
Nimonic 75, 4 hr at 750 C, air cooled	22	0.441	4.7	0.187	0.285	5.2	0.187	64.6
	16	1.478	2.9	0.246	0.997	2.2	0.250	67.4
Nimonic 75, 1/4 hr at 1000 C, air cooled;	22	0.462	2.5	0.182	0.279	4.4	0.187	60.4
4 hr at 750 C, air cooled	16	1.500	7.4	0.250	1.006	2.2	0.248	67.0
Nimonic 80A, 4 hr at 750 C, air cooled	22	0.696	2.6	0.183	0.236	3.3	0.185	33.85
	16	2.138	3.8	0.250	0.913	5.8	0.245	42.68
Nimonic 80A, 1/2 hr at 1080 C, air cooled;	22	0.702	4.2	0.183	0.28	4.1	0.187	39.81
1 hr at 950 C, air cooled; 4 hr at 750 C, air cooled	16	2.159	1.6	0.247	1.01	6.7	0.250	46.78
Nimonic 90, 4 hr at 750 C, air cooled	22	0.719	4.9	0.186	0.248	4.1	0.187	34.5
	16	1.707	5.7	0.250	0.843	2.9	0.250	49.4
Nimonic 90, 1/2 hr at 1080 C, air cooled;	22	0.716	4.3	0.186	0.219	9.7	0.185	30.8
1 hr at 950 C, air cooled; 4 hr at 750 C, air cooled	16	1.942	2.6	0.250	0.933	2.1	0.249	48.0

Brazing

The brazing of age-hardenable nickel-base alloys presents a different and a much more complex problem than the brazing of other nickel-base alloys. In industry where these alloys must be brazed they are called "problem" alloys. The problem arises because they contain aluminum and/or titanium. In general, the magnitude of the problem varies directly with the sum of the amount of these elements present. The difference between lower and higher levels of aluminum and titanium, however, does not warrant concern because it is best to use the brazing procedure which assures good brazing under the worst possible conditions. Therefore, no attempt will be made to distinguish between brazing procedures for each of the several age-hardenable nickel-base alloys.

In this section, the discussion will be limited to the use of high-temperature oxidation-resistant brazing filler metals. This is because they are the only materials compatible with the uses to which most age-hardenable nickel-base alloys are subjected. The discussion on the interactions between base metals and filler metals is applicable to solid-solution-strengthening and nonaging alloys if these filler metals are used on them.

The age-hardening nickel-base alloys have titanium and aluminum oxides on their surfaces. These oxides cause difficulty because they are easily formed on exposure to air or other oxidizing conditions and cannot be reduced by even very dry pure hydrogen atmospheres. Chang[47] has shown by thermodynamic calculation that a hydrogen atmosphere must have a dew point lower than -110 F at 2000 F in order to reduce titanium oxide. He also shows that even drier hydrogen is needed to reduce aluminum oxide. In practice, even drier atmospheres seem necessary. A plot of Chang's data is given in Figure 17. It is not practical to attempt to reduce the oxides on age-hardening nickel-base alloy by using a hydrogen atmosphere at the temperatures suitable for these alloys. Torch brazing with a flux or other simple "open-air" brazing methods are usually impractical for the same reason. Titanium/aluminum oxides form too readily and are not removed by ordinary fluxing techniques.

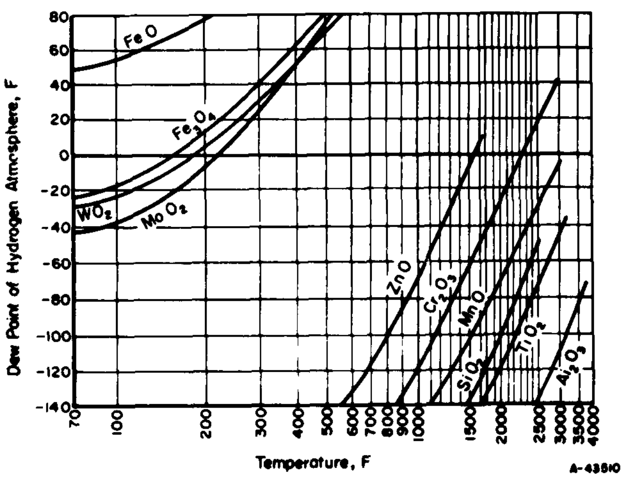


FIGURE 17. METAL-METAL OXIDE EQUILIBRIUM IN HYDROGEN ATMOSPHERE[47]

The necessity for fabricating high-temperature, high-strength, nickel-base alloys into useful parts by brazing has forced the expenditure of much effort on the development of brazing techniques. The results of this effort have shown that the problem alloys can be satisfactorily brazed by a number of techniques. The more important of these are:

(1) Vacuum brazing at pressures of 2 microns or lower

(2) Hydrogen brazing aided by a high-temperature flux such as sodium fluoride

(3) Hydrogen brazing aided by a precoating of electroplated nickel or iron

(4) Hydrogen brazing aided by a titanium- and aluminum-depleted surface obtained by preoxidizing the base-metal surface and leaching out the oxides

(5) Hydrogen brazing aided by the preplacement of the filler metal by flame spraying.

Huschke and Hoppin[48] studied each of these techniques on several high-strength base metals, including some of the age-hardening nickel-base alloys. Their work led to the conclusion that vacuum brazing is the most suitable brazing procedure. Their plot of the strength of joints in Hastelloy R-235 (Figure 18) was only part of the justification for their conclusion. The joints made with an electroplated base metal were weakest because of the nickel interface. Also, electroplating is expensive, does not lend itself well to all configurations, and the plating thickness required varies with other process variables. Joints made with flux were weaker than vacuum-brazed joints because of flux entrapment. Flux residues are hard to remove and may cause corrosion problems. The leaching technique is adaptable only to small parts which can be heated rapidly and not to the furnace brazing of large parts. This process is heating-rate sensitive; that is, the titanium and aluminum may increase at the surface by diffusion during heating. Flame spraying to preplace the brazing filler metal is suitable for some shapes, but not for others. Also, brazing-filler-metal flow is nil when using this technique.

The above discussion indicates the reason for the widely preferred practice of using a vacuum-brazing procedure when joining age-hardening nickel-base alloys containing aluminum and/or titanium. The real advantages, however, are available mainly to fabricators of large and complex assemblies. Small furnaces, special base-metal-preparation procedures, and gas-atmosphere systems have been satisfactory for brazing small assemblies. The usefulness of a combination of both vacuum and hydrogen or inert atmospheres has also been demonstrated.[49] Convair has brazed honeycomb panel specimens from R-41 in the laboratory in an argon atmosphere.[50] They report that the major obstacle to successful brazing was obtaining a suitably purified argon.

The presence of titanium and/or aluminum in age-hardenable nickel-base alloys is not the only problem encountered when brazing these alloys. The interactions between the base metal and the brazing filler metal at or near brazing temperature must also be recognized. Practically all of the constituents of the more common high-temperature, nickel-base brazing filler metals react with nickel-base base metals.

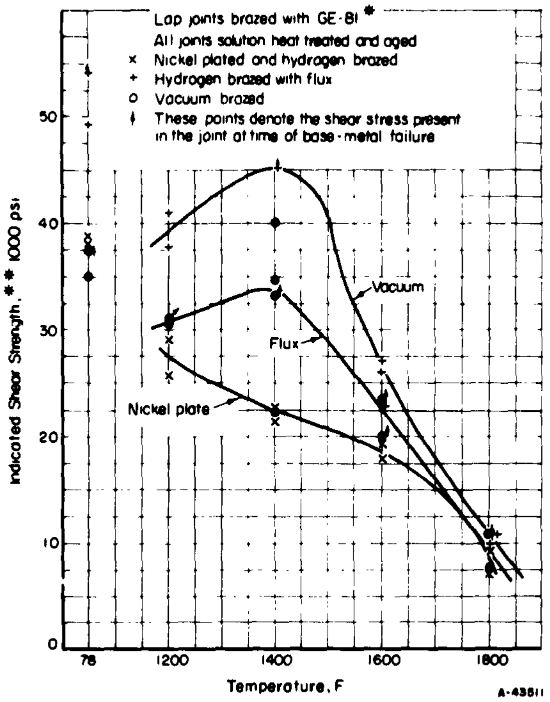


FIGURE 18. INDICATED SHEAR STRENGTH VERSUS TEMPERATURE FOR HEAT-TREATED BRAZED JOINTS IN HASTELLOY R-235[48]

Feduska[51] has reported on the diffusion of the constitutents of nickel-base brazing filler metal into several heat-resistant alloys. One of these alloys was Inconel X. Conclusions important to this discussion were as follows:

(1) Carbon, boron, and sometimes silicon rapidly diffuse along grain boundaries at brazing temperatures between 1740 and 2190 F. These elements (a) "irrigate" into adjoining grain regions, (b) also move by volume diffusion into the base-metal surface grains, and (c) react with base-metal elements to form borides, carbides, and silicides.

(2) Chromium, iron, nickel, and generally silicon penetrate slowly by volume diffusion and form solid solutions with base-metal constituents.

(3) The observed diffusion mechanisms were in accordance with bonding reactions encountered when studying commercial brazing-filler-metal reactions with the same base metals.

(4) Sometimes, diffusing silicon reacts with nickel to form a nickel-silicon rich eutectic on the base-metal surface.

The practical aspects of these conclusions are manifest most when it becomes necessary to braze assemblies with relatively thin cross sections or when vibrational loading is anticipated. Penetration of elements which reduce the effective thickness of ductile

base metal and replace it with nonductile metal compounds is not tolerable. Erosion or dissolution of the base metal is also encountered when brazing nickel-base alloys. This too is intolerable, especially in thin sections.

A great amount of effort has been expended in overcoming the problems arising from the interactions between nickel-base alloys and nickel-base filler metals. Solutions have been found, but none are completely satisfactory in all respects.

Electroplating is one apparent solution, especially since it also aids in overcoming the effects of titanium and aluminum oxides. At General Electric, electroplating of R-41 with nickel did reduce erosion and grain-boundary penetration,[29] but the resultant joints were weaker than joints brazed without plating in a vacuum. Table 34 presents the results of one such study. These data might also be used to show that vacuum brazing gives a stronger joint than hydrogen brazing and that the nickel plate is not the cause of the difference. Such conclusions have been made and have become the subject of some controversy. There is no fundamental reason why vacuum-brazed joints should be stronger than hydrogen-brazed joints. The differences are caused by an inability to produce the extremely dry hydrogen atmospheres needed for these alloys in ordinary furnaces.

Another means for minimizing the interaction between the base metal and the brazing filler metal involves strict control of the amount of brazing filler metal used, and strict control of the brazing temperature cycle. The practice of very carefully controlling these two variables is probably the most widely used method of limiting the undesirable interactions. This practice simply does not permit the conditions for much interaction to occur.

Most of the high-temperature brazing filler metals are powders. This permits the use of another method to control filler metal-base metal reactions. Pure metal powders, such as nickel, or powder having the base-metal composition added to the filler metal, inhibit reaction with the base metal. This technique has not been widely used.

Many investigations have been undertaken to develop brazing filler metals which fulfill all other requirements and do not react with the nickel-base metal. A few of these have been successful, but have not been widely accepted because they are high in expensive noble metal (gold and palladium) content, or do not always have the desired strength and oxidation resistance. One such filler metal has been used for some time but was only recently reported in the literature. It may overcome some of the cited disadvantages.[52] Its composition is 33 per cent chromium, 24 per cent palladium, 4 per cent silicon, balance nickel. It has been designated J-8600 by the developer, The General Electric Company. The average properties of joints made with J-8600 in René 41 are given in Table 35. Similar results were obtained when this brazing filler metal was used on Inconel X and the solid-solution-strengthening alloy Hastelloy X. Other investigators have also reported on the development of filler metals.

Inconel 718 can be brazed relatively easier than can most nickel-base alloys hardened by the precipitation of aluminum and/or titanium compounds. The lower concentration of these oxide-forming elements permits the practice of brazing procedures similar to those used for the precipitation-hardening stainless steels.

TABLE 34. STRENGTH OF BRAZED LAP JOINTS IN R-41 SHEET[29]

Brazing alloy, AMS 4775 (Ni, Cr, B, Si, Fe)
Clearance, 0.002 inch
Nominal overlap, 0.100 inch
Brazing temperature, 2150 F
Brazing time, 10 minutes

Test Temperature, F	Cleaned and Vacuum Brazed: Indicated Shear Stress[a], psi	Cleaned and Vacuum Brazed: Indicated Tensile Strength, psi	Cleaned and Vacuum Brazed: Failure Location	Nickel Plated and Hydrogen Brazed: Indicated Shear Stress, psi	Nickel Plated and Hydrogen Brazed: Indicated Tensile Strength[b], psi	Nickel Plated and Hydrogen Brazed: Failure Location
78	38,000	62,000	PM[c]	31,000	53,000	Braze
78	29,000	45,000	PM	29,000	59,000	Braze
1200	37,000	56,000	PM	26,000	52,000	Braze
1200	37,000	60,000	PM	32,000[a]	58,000	PM
1400	27,000	44,000	PM	24,000	38,000	Braze
1400	28,000	45,000	PM	15,000	28,000	Braze
1600	46,000	74,000	PM	15,000	23,000	Braze
1600	41,000	66,000	PM	12,000	20,000	Braze
1800	22,000	36,000[b]	Braze	5,000	10,000	Braze
1800	22,000	35,000	PM	6,000	9,000	Braze

(a) Shear stress for load at tensile failure.
(b) Tensile stress for load at shear failure.
(c) Parent metal.

TABLE 35. AVERAGE SHEAR-STRENGTH PROPERTIES OF BRAZED UNPLATED RENÉ 41 (0.063 INCH THICK)[52]

Close tolerance lap joints
J8600 brazing filler metal
Brazed at 2150 F in a vacuum
Heat treated after brazing[a]

Test Temperature, F	Joint Area, square inch	Ultimate Load,[b] lb	Indicated Shear Strength,[c] psi
RT	0.054	1885	35,250
700	0.044	2120	48,400
1250	0.054	2050	38,200
1450	0.058	2165	37,150
1700	0.049	220	4,580

(a) 1950 F - 1/2 hour - R.A.C.; 1400 F - 16 hours - A. C.
(b) All failures in the braze.
(c) Ultimate load divided by joint area.

The above discussion of the brazing of age-hardenable nickel-base alloys may seem unduly pessimistic. It is not intended this way. It must be noted that with due cognizance of the characteristics of all the materials involved many complex structures have been built which have withstood very severe service conditions. This discussion has shown that the base metal, the brazing filler metal, and the procedures for brazing must be selected very carefully. A thorough understanding of the physical metallurgy of the base metal-filler metal interactions is necessary. In addition, effect of brazing thermal cycles on the properties of the age-hardenable nickel-base metal must be determined. If this effect is significant design changes may be necessary. The degradation of the strength of nickel-base age-hardenable alloys as a result of the brazing thermal cycle has been studied by several investigators.[29,53,54]

JOINING OF NICKEL-BASE ALLOYS TO OTHER METALS

Sometimes it is necessary to join the nickel-base alloys to alloys of lower nickel content or to other metals such as stainless steel or carbon steel. This may be done by welding, brazing, soldering, or it may be done mechanically. The preferred methods are welding and brazing. Soldering is usually suitable only for joints which carry very little or no load at room temperature. Mechanical joints require more space, add weight, and, if adequate for the job, may be more expensive.

The problems which arise from the desire to make dissimilar metal joints depend mainly on the difference in composition between the alloys. If they are similar or are metallurgically compatible over a wide composition range, problems will not be great, assuming that good welding practice is used.

An example of the ideal metallurgical situation is the welding of pure nickel to Monel. These metals are completely compatible. Consequently, they can be welded to one another by any process using any compatible filler material without fear of difficulty.

In other situations, dilution of the nickel-base alloy with a dissimilar metal during welding can be tolerated only to a limited degree. Wilson and Birchfield[21] cover this case very well, using the example of Monel to austenitic stainless steel welding. If stainless steel filler wires are used, any significant copper pickup from the Monel will cause the weld to become hot short and crack in the weld. Thus stainless steel filler wire should be avoided for this couple when processes which cause much dilution are used. Likewise, a Monel filler wire is not useful because chromium from the stainless will cause cracking. A special Inconel filler wire or nickel are best but are not foolproof.

From the discussion above, it is apparent that the dilution obtained during the welding of nickel-base alloys to other metals is very important. Processes which result in a minimum of dilution should always be used. Manipulation of the arc to impinge mainly on the base metal which is nearest in composition to the filler wire will assist in minimizing dilution. Suppliers of filler wire and electrodes should be consulted before a choice is made for any particular dissimilar-metal combination.

The International Nickel Company Technical Bulletin T-2[4] indicates that these weld compositions should be avoided.

(1) A ferritic weld deposit if dilution by nickel, chromium, or copper is to be encountered

(2) The 18-8 type weld deposit if dilution by more than 3 per cent copper is to be encountered

(3) A high-carbon Monel deposit if dilution by iron is to be encountered

(4) Any Monel deposit if dilution by more than 6-8 per cent chromium is anticipated

(5) The 18-8 type deposit if dilution by nickel and chromium is sufficient to result in the crack-sensitive 35Ni-15Cr weld composition.

Bland and Owczarski[55] investigated the arc welding of Inconel to Type 304 stainless steel, carbon steel, and to itself. Base-metal plate thicknesses from 0.75 to 2.63 inches were welded, using the shielded-metal-arc, inert-gas tungsten-arc, and inert-gas metal-arc processes. They obtained welds by all processes which met the stringent requirements for nuclear-power-plant service. Included in the data published are strength at room temperature and at 650 F, hardness, and bend ductility. This study also included overlaying of Inconel on other base metals. Witherell[56] has made a similar study of the welding of heavy Inconel plate to carbon steel plate utilizing specific nickel-base electrodes, MIL-4N85 for covered electrode welding and

MIL-EN87/RN87 for inert-gas metal-arc welding. The weld deposit compositions of these electrodes for use when welding or overlaying are given here.

Electrode	Composition, per cent										
	Ni	Cr	Fe	Mn	Cb+Ta	C	Ti	Si	S	Cu	Co
MIL-4N85	67.0	14.7	7.5	7.7	2.0	0.04	0.40	0.50	0.007	0.03	0.07
MIL-EN87/RN87	72.0	20.0	1.0	3.0	2.6	0.03	0.30	0.30	0.009	0.02	0.04

Crack- and porosity-free welds were obtained under every condition examined: position, heat treatment, high restraint, and use on weld metal.

Another electrode reported useful for making transition welds between Inconel and stainless steel was reported by Fragetta and Pease.(57) A titanium-manganese modified Inconel weld wire was used with the inert-gas metal arc to produce high-quality welds in heavy plate.

Carey(27) welded age-hardened Inconel W 1-inch-thick to Inconel of the same thickness and met all the requirements for a naval nuclear application. Both the manual and inert-gas tungsten-arc processes were used. Hardness data only are given, but tension, bend, and other tests were made.

During the production of retorts for high-temperature furnaces, Johnson(58) reports that Hastelloy X is welded to itself, to Inconel, and to mild steel. The same practice is used for the dissimilar-metal systems as when welding Hastelloy X to itself, but a different filler metal is used (Inco-Weld "A"). Heat input is kept at a minimum by: discrete joint design, single-pass welding, minimum weaving, fast travel speeds. The thicknesses welded are 0.25 and 0.38 inch.

In the foregoing discussion the importance of two things is quite apparent when welding nickel-base alloys to other metals; dilution of the weld metal, and proper filler-metal choice. The two factors are strongly interrelated and have led to the development of new and altered filler metals as indicated.

The welding of the age-hardenable nickel-base alloys to other metals is not well covered in the literature. Such joints are made, however, with considerable success as long as the accepted procedures and proper filler metals are used. Hastelloy W has been used widely as a filler metal for welding dissimilar combinations. It was developed for this purpose. The composition of Hastelloy W is essentially the same as that of Hastelloy B, but with 5 per cent additional chromium. This composition provides an ideal matrix when used to weld many different dissimilar age-hardenable alloy combinations.

REPAIR WELDING OF NICKEL-BASE ALLOYS

Repair welding is an important phase in the fabrication of many nickel-base alloys. During the development of procedures for welding these alloys, consideration should always be given to the possibility that repair welding may be necessary. This is especially true in the case of the solid-solution-hardening and age-hardening alloys, because

the cost of the base metal and of preparing it for welding is very high. Also, the complex structures usually involved are not amenable to complete stress analysis prior to welding.

The repair of the nonaging nickel-base alloys does not usually present serious problems. Analysis of the cause of the defect, its complete removal, and then repair welding utilizing the original procedure altered to eliminate the cause of the defects will usually suffice. Most of the solid-solution- and age-hardening nickel-base alloys are much more difficult to repair weld. The extra thermal cycling due to rewelding and the heat treatments necessary must be carefully developed for the situation at hand.

A few general rules applicable to the repair welding of all nickel-base alloys are outlined below. If they are followed, problems will be minimized.

(1) Inspect for repairable weld flaws immediately after welding and before any subsequent treatment.

(2) Determine the cause of flaws before repairing so that procedure modifications can be made if necessary. Examine also the mechanical design of the joint. Will it permit complete removal of the flaw? Is the design the cause of the flaw?

(3) Determine whether or not the flaw can or should be repaired. The repair weld is a heterogeneous area in the weld and as such may continue to function as a flaw.

(4) Remove entire flaw and prepare the joint area as in original or modified procedure.

(5) Repair weld on metal that is as nearly as possible in the same condition as when originally welded.

(6) Make provisions for local or complete stress relief where necessary.

(7) If repair welds must be made on material which has been given its final heat treatment, develop repair procedures on an experimental basis.

Much of the literature on the welding of nickel-base alloys indicates the need for and successful accomplishment of repair welds in these alloys. Very little has been published on the details of the procedural changes required. This is taken as an indication that, in many cases, successful repair welding is an art which depends on the skill of the welder and the experience of the welding and metallurgical engineers involved.

Procedures have been published on one technique for repair welding René 41.[59] The main objective was to develop techniques that would prevent cracking during subsequent heating in the temperature range where the ductility of the alloy was low. The restrained-type circular-patch test was used. All repair welds were made on specimens that had been welded, solution treated, and aged. After repair welding, the weldments were subjected to cyclic heating similar to that occurring in jet-engine operation. The best methods for preventing cracking in René 41 repair welds were:

(1) Locally solution treating the repaired weld at 1950 F for 5 minutes

(2) Cold working the surface of the repaired weld by hammer peening at room temperature.

Both operations were performed before aging the repaired weld. The effect of hammer peening was to refine the grain size, and perhaps reduce residual stresses.

Three other repair-weld heat-treatment sequences for René 41 have been reported:

(1) Repair, solution treat, then use a double aging treatment, 1650/1400 F

(2) Repair, anneal at 1800 F, air cool, then age

(3) Repair, age, then furnace cool.

The particular attributes of these treatments were not given.

Boeing[17] examined the repairability of René 41 on test assembly parts containing lap joints. Attempts to make these welds in the aged alloy were not successful when René 41 filler metal was used. Sound joints were obtained by using Hastelloy W filler metal. Manual welding was used. Synthetic defects were filled with weld metal while the heat input was gradually tapered off to produce suitable weld contours.

Lepkowski, et al.,[59] also made some tests on the repair welding of Astroloy. Some difficulty in producing crack-free original welds in their restrained specimen was encountered. By peening both immediately after welding and after solution treatment, suitable welds were made. Then, crack-free repair welds on the aged specimens were obtained by peening for 1 minute before reaging.

Weiss and Hacker[60] in discussing the repair welding of age-hardenable alloys cite these important considerations.

(1) Weld heat input

(2) Weld backing media

(3) Filler-material selection

(4) Postweld heat treatments

(5) Special welding and grinding equipment.

They have incorporated the use of specially shaped furnaces for heating only those areas that have been repaired as a standard procedure for many repair welding applications.

Inconel 718 is a nickel-base high-strength alloy that can be repair welded with relatively little difficulty. This is directly attributable to the different hardening mechanism mentioned previously. It can also be welded in the age-hardened condition.

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